



(12) **United States Patent**
Reynolds et al.

(10) **Patent No.:** **US 9,281,769 B2**
(45) **Date of Patent:** **Mar. 8, 2016**

(54) **ELECTRONIC CIRCUIT AND METHOD FOR ADJUSTING START-UP CHARACTERISTICS OF DRIVE SIGNALS APPLIED TO AN ELECTRIC MOTOR**

(71) Applicant: **Allegro Microsystems, LLC**, Worcester, MA (US)

(72) Inventors: **Timothy Reynolds**, Westborough, MA (US); **Chengyi Jin**, Wayland, MA (US)

(73) Assignee: **Allegro Microsystems, LLC**, Worcester, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 300 days.

(21) Appl. No.: **13/893,671**

(22) Filed: **May 14, 2013**

(65) **Prior Publication Data**

US 2014/0340008 A1 Nov. 20, 2014

(51) **Int. Cl.**
H02P 6/20 (2006.01)
H02P 6/18 (2006.01)
H02P 1/52 (2006.01)

(52) **U.S. Cl.**
CPC **H02P 6/205** (2013.01); **H02P 1/52** (2013.01);
H02P 6/182 (2013.01); **H02P 2209/11** (2013.01)

(58) **Field of Classification Search**
USPC 318/430–433, 400.11, 400.2
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,134,050 A * 1/1979 Sibalís 318/267
4,409,533 A 10/1983 Kawabata

5,006,778 A * 4/1991 Bashark 318/799
6,172,475 B1 * 1/2001 Fitzgibbon et al. 318/266
7,034,478 B2 4/2006 Bhaumik et al.
7,531,976 B2 5/2009 Fukamizu et al.
7,590,334 B2 9/2009 Yabusaki et al.
7,747,146 B2 6/2010 Milano et al.
8,405,332 B1 3/2013 Krishnamoorthy et al.
2006/0222345 A1 10/2006 Wood
2009/0167220 A1 7/2009 Kanamori
2011/0115423 A1 5/2011 Kern et al.
2013/0009578 A1 1/2013 Reynolds et al.

FOREIGN PATENT DOCUMENTS

CN 101026351 A 8/2007
JP 2008 245411 A 10/2010
WO WO 2009/020737 A2 2/2009

OTHER PUBLICATIONS

U.S. Appl. No. 13/599,225, filed Aug. 30, 2012, Reynolds et al.
U.S. Appl. No. 13/599,234, filed Aug. 30, 2012, Reynolds et al.
PCT Search Report and Written Opinion dated Aug. 28, 2014; for PCT Pat. App. No. PCT/US2014/035825; 14 pages.

(Continued)

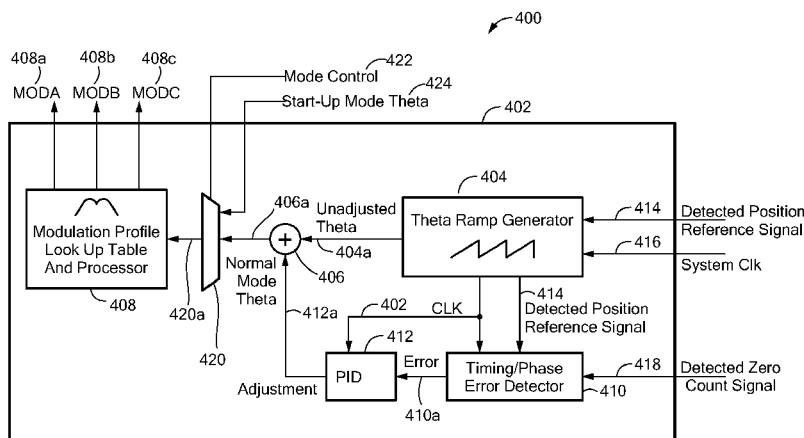
Primary Examiner — Bentsu Ro

(74) *Attorney, Agent, or Firm* — Daly, Crowley, Mofford & Durkee, LLP

(57) **ABSTRACT**

A motor control circuit and associated techniques can drive an electric motor in a start-up mode of operation followed by a normal mode of operation. The motor control circuit and techniques can receive a selection signal provided by a user that can select one of a plurality of sets of parameter values that determine characteristics of drive signals applied to the motor during the start-up mode of operation. The motor control circuit and associated techniques can synchronize operation between the start-up mode of operation and the normal mode of operation.

36 Claims, 15 Drawing Sheets



(56)

References Cited

OTHER PUBLICATIONS

PCT Search Report and Written Opinion of the ISA dated Jan. 26, 2015; for PCT Pat. App. No. PCT/US2014/035820; 9 pages.
Taiwan Office Action and Search Report (English translation); for Taiwan Pat. App. No. 103116100; dated Jul. 14, 2015; 6 pages.
Notice of Allowance dated Jun. 25, 2013; for U.S. Appl. No. 13/893,678; 12 pages.
Taiwan Office Action and Search Report (English translation) dated Jul. 28, 2015; for Taiwan Pat. App. No. 103116102; 10 pages.

Response with English translated dated Oct. 15, 2015 for Taiwanese Office Action dated Jul. 14, 2015; For Taiwanese Pat. App. No. 103116100; 42 pages.

Response to Chinese Office Action with English Claims and Specification dated Oct. 29, 2015; For Chinese Pat. App. No. 103116102; 39 pages.

PCT International Preliminary Report on Patentability and Written Opinion of the ISA dated Nov. 26, 2015; For PCT App. No. PCT/US2014/035825; 12 pages.

PCT International Preliminary Report on Patentability and Written Opinion of the ISA dated Nov. 26, 2015; For PCT App. No. PCT/US2014/035820; 5 pages.

* cited by examiner

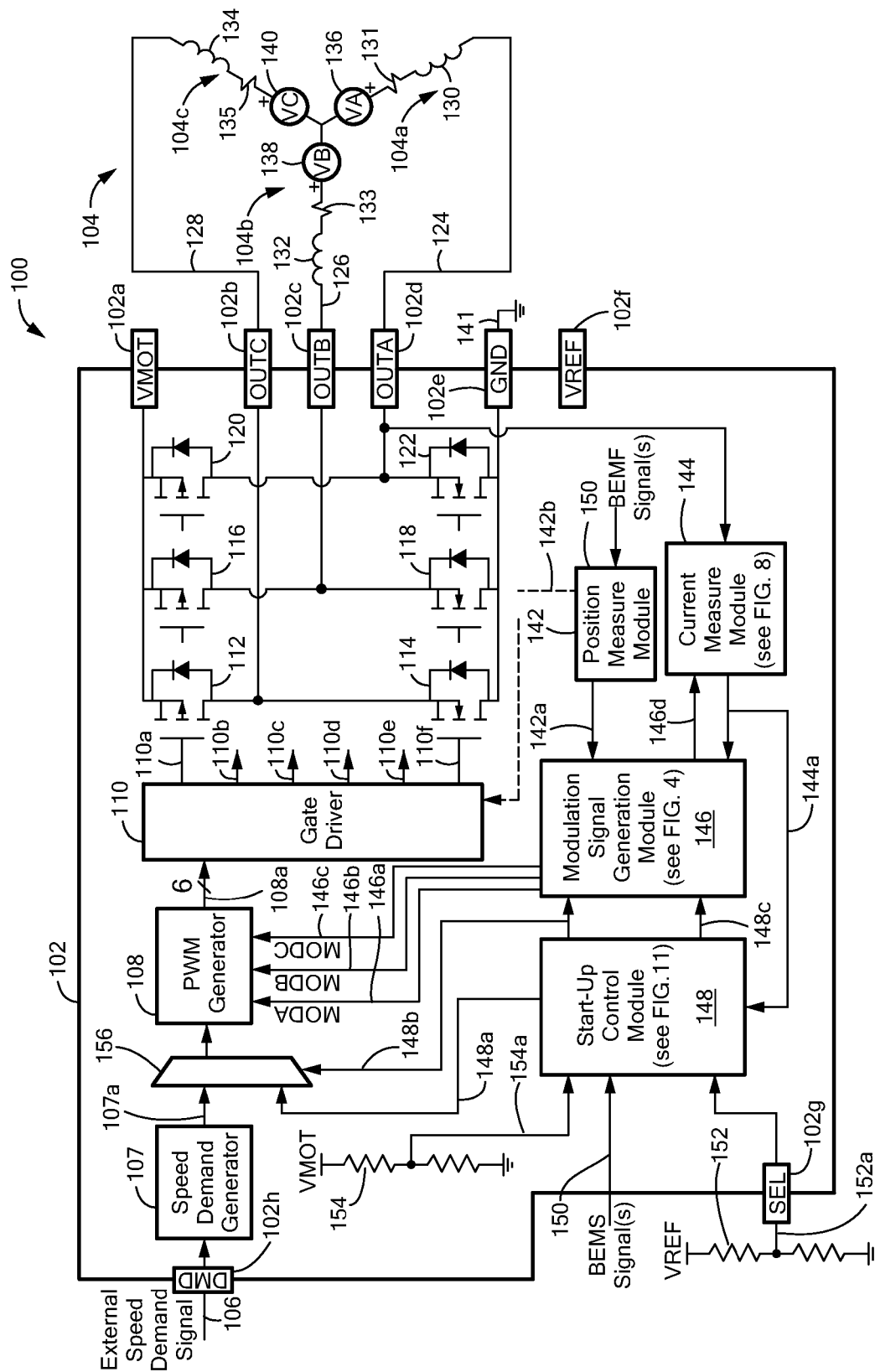


FIG. 1

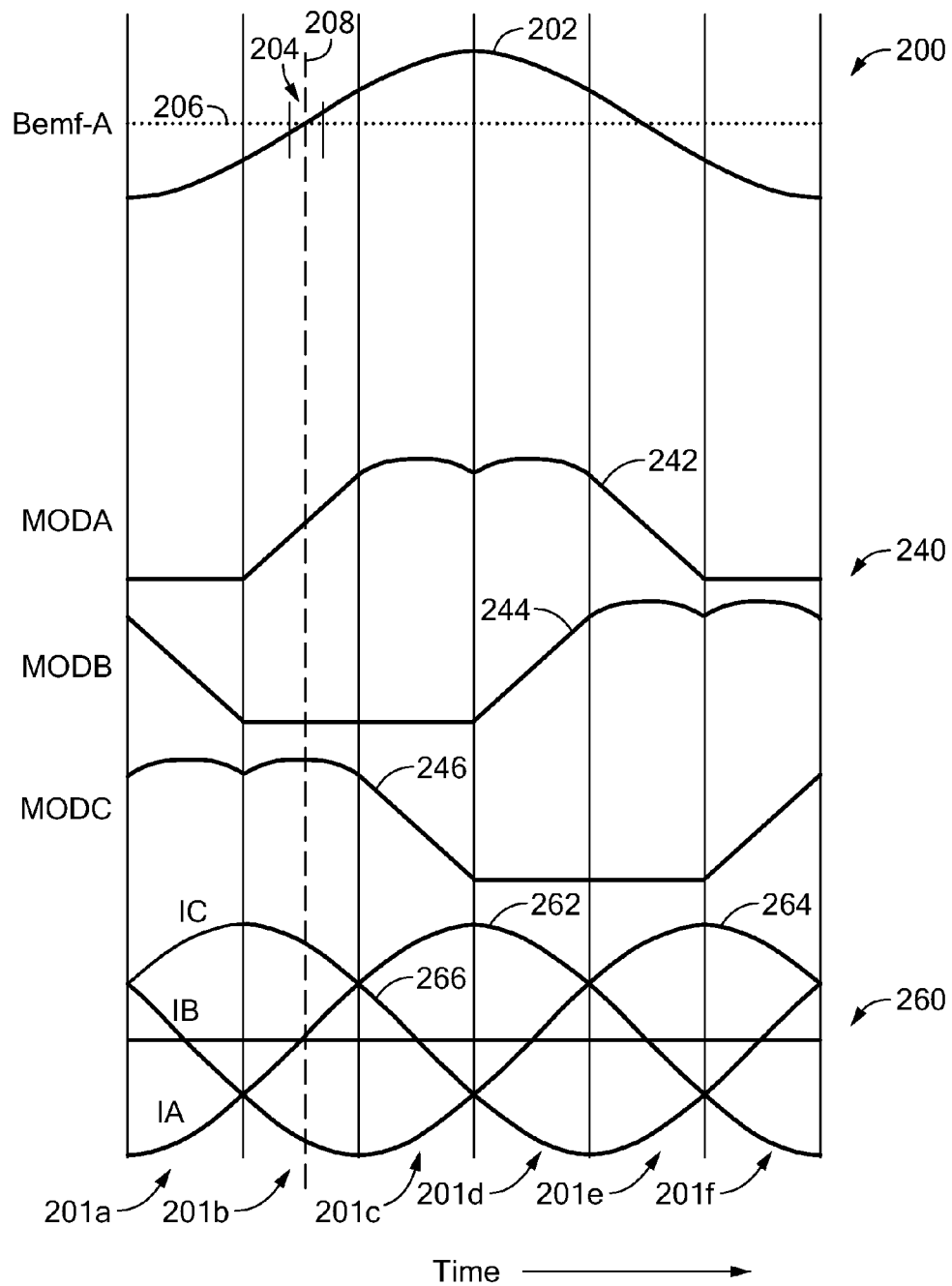


FIG. 2

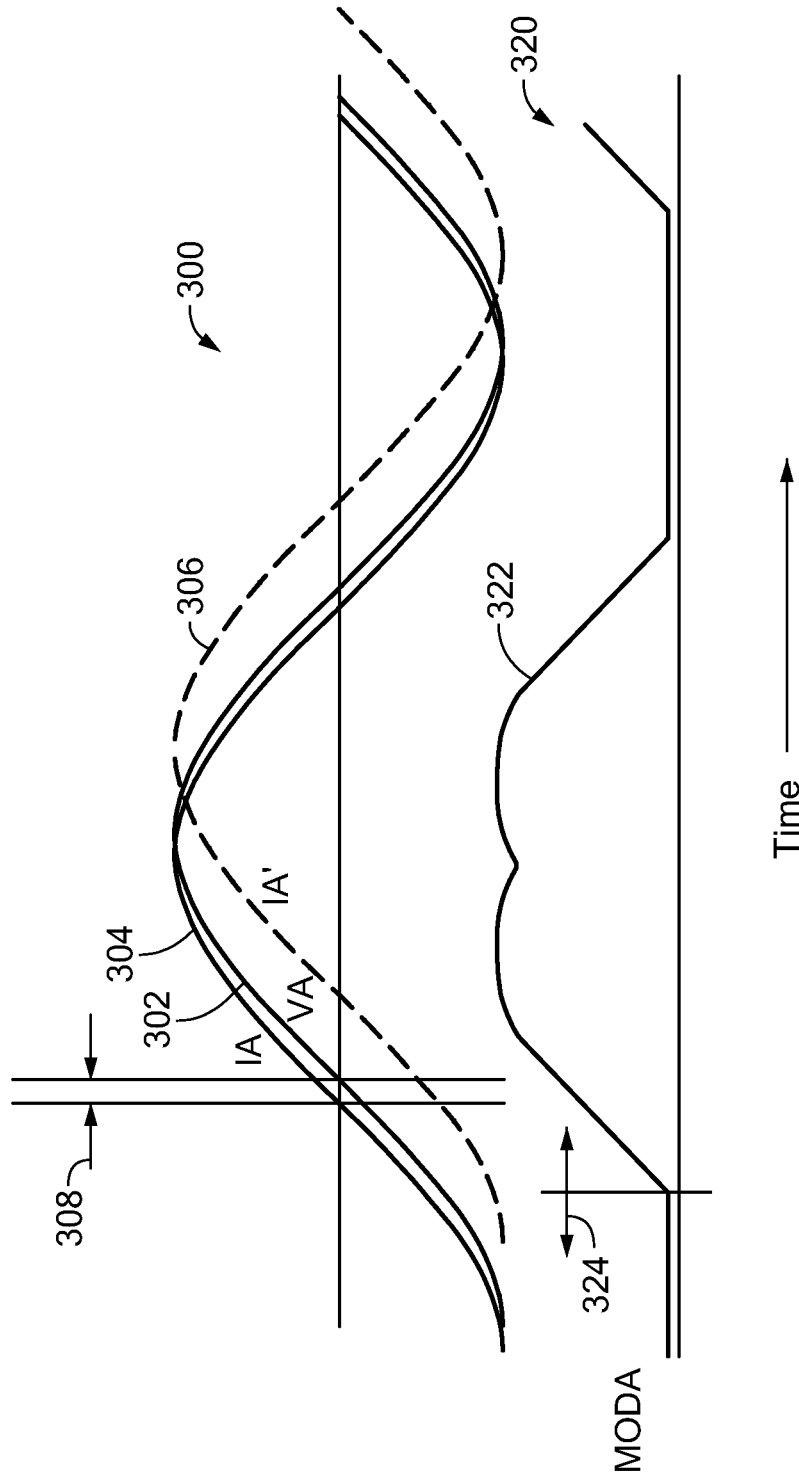


FIG. 3

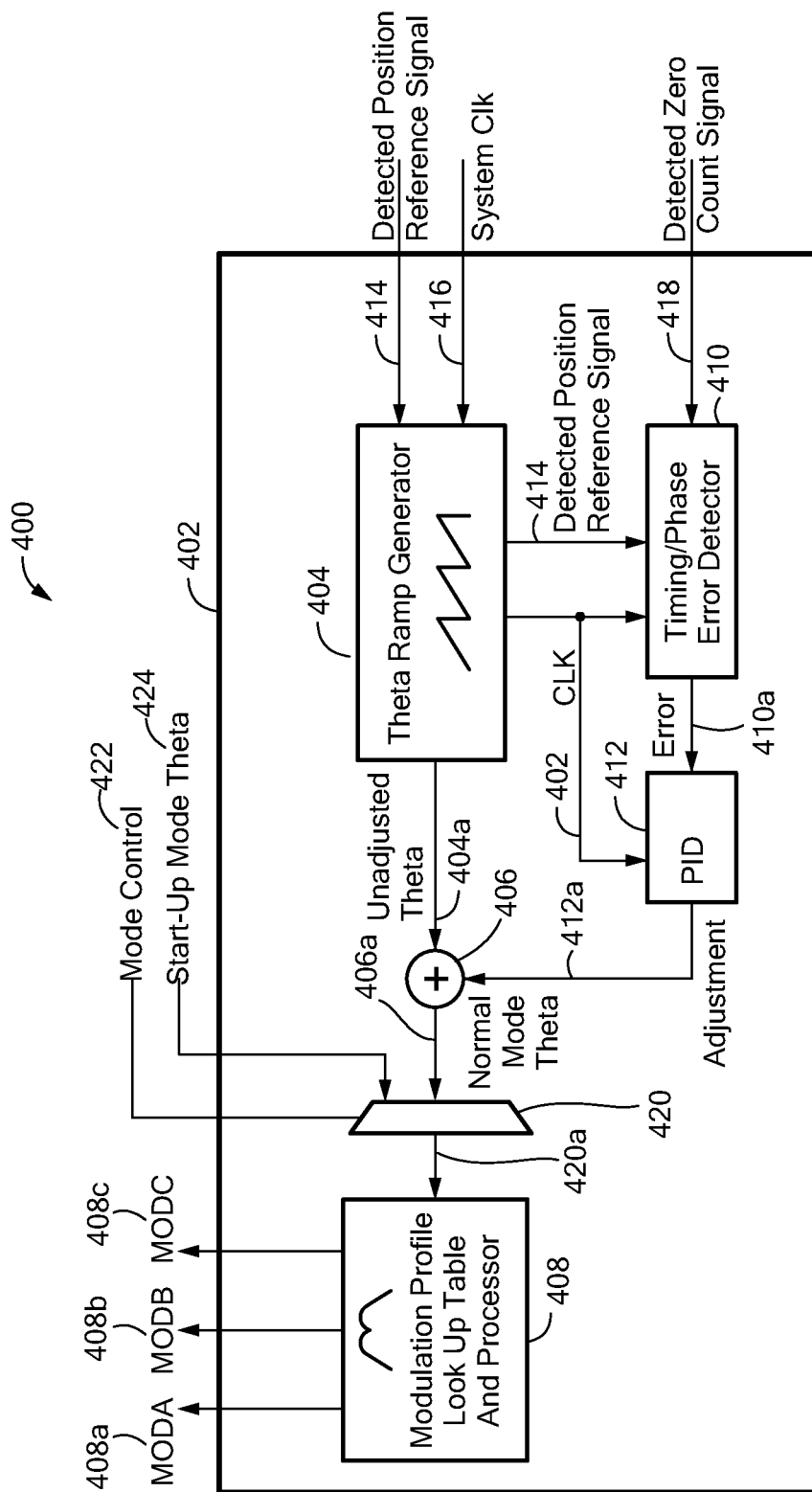


FIG. 4

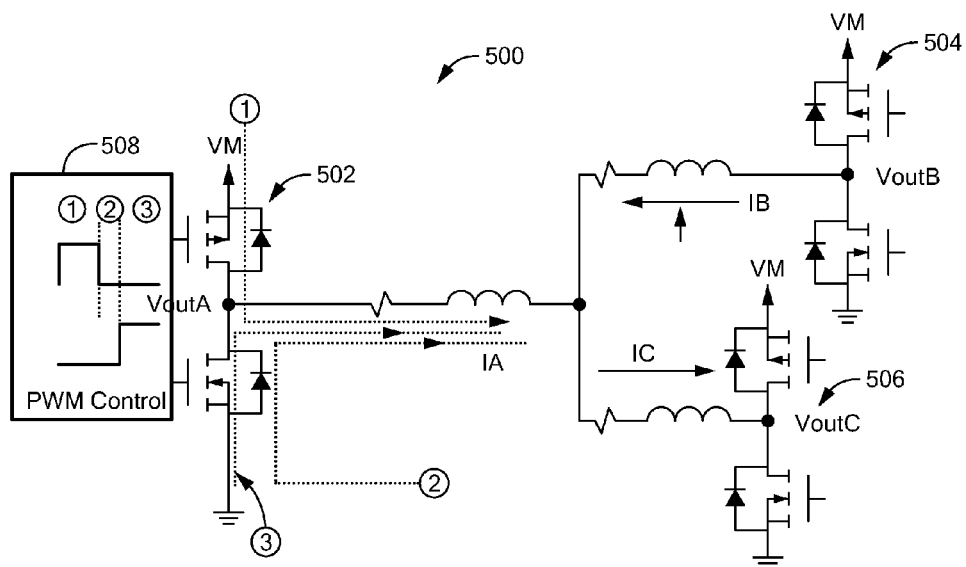


FIG. 5

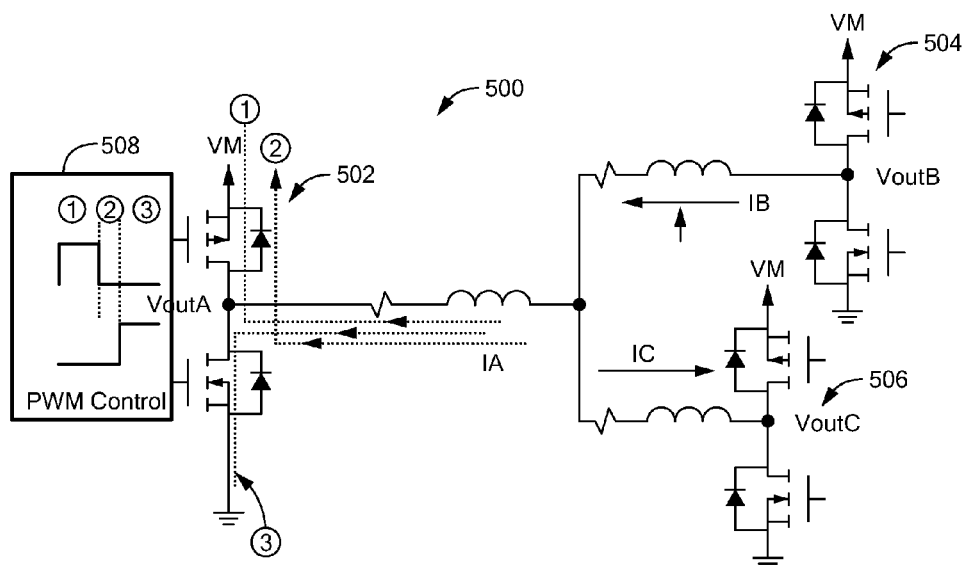


FIG. 5A

FIG. 6

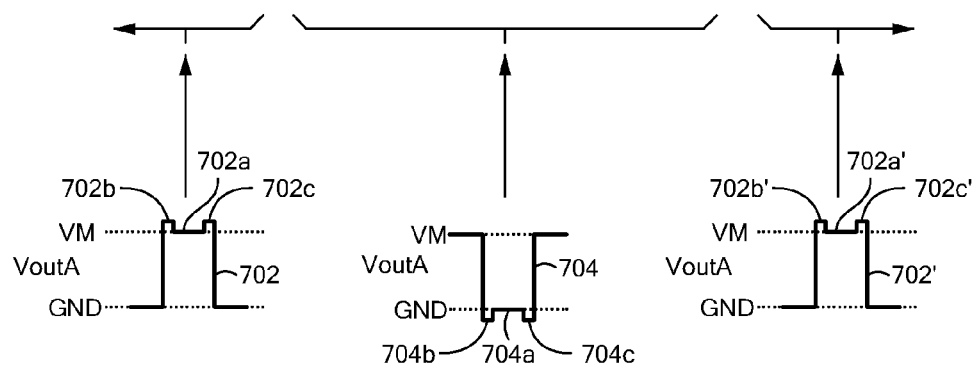
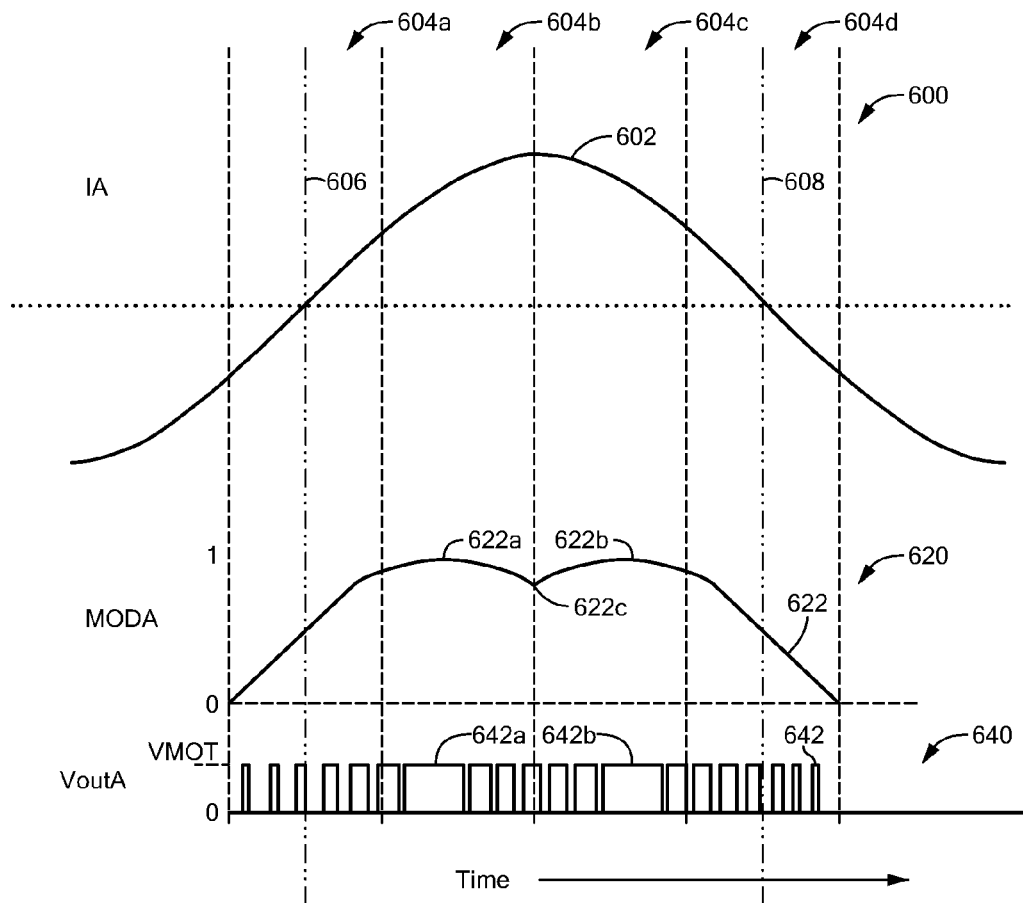


FIG. 7

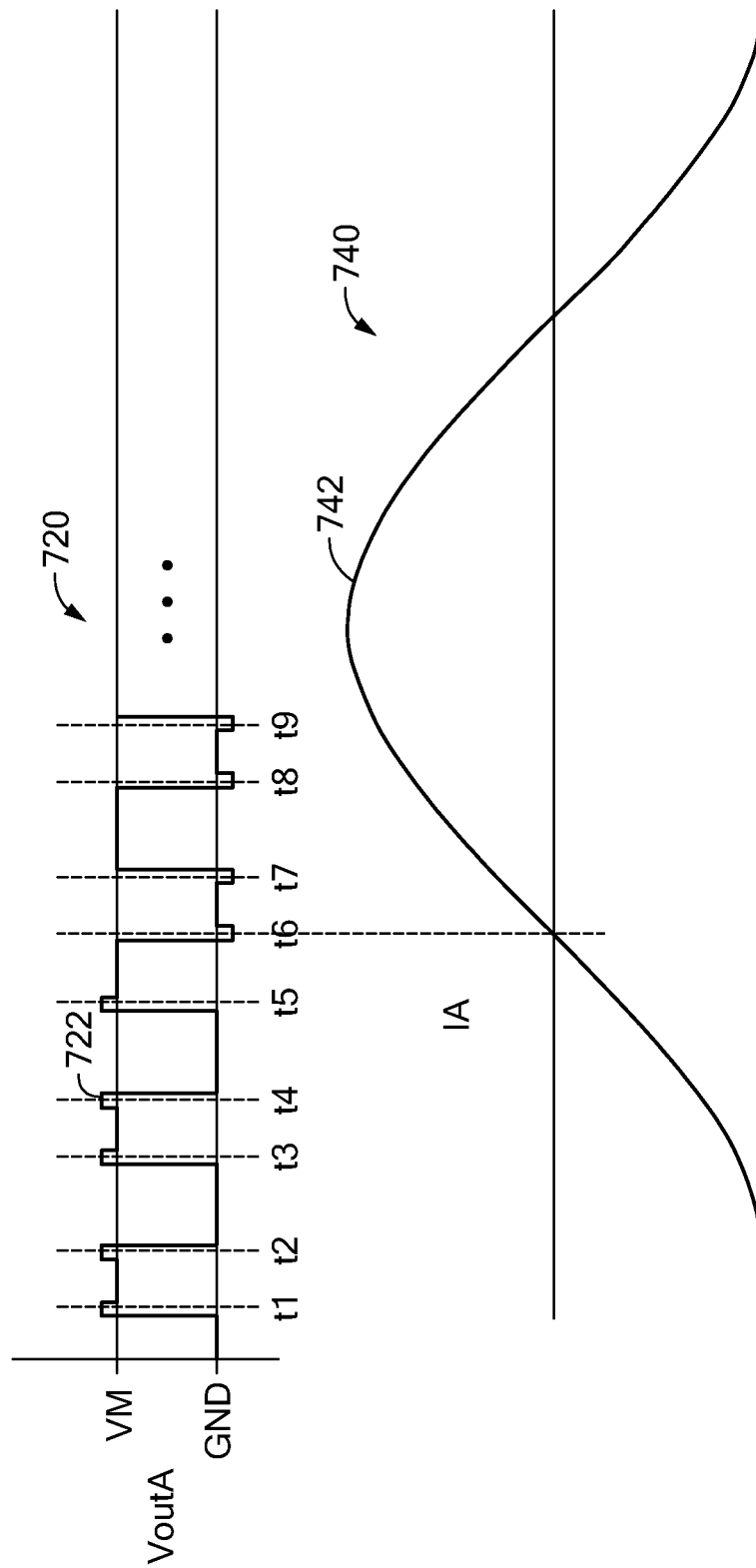


FIG. 7A

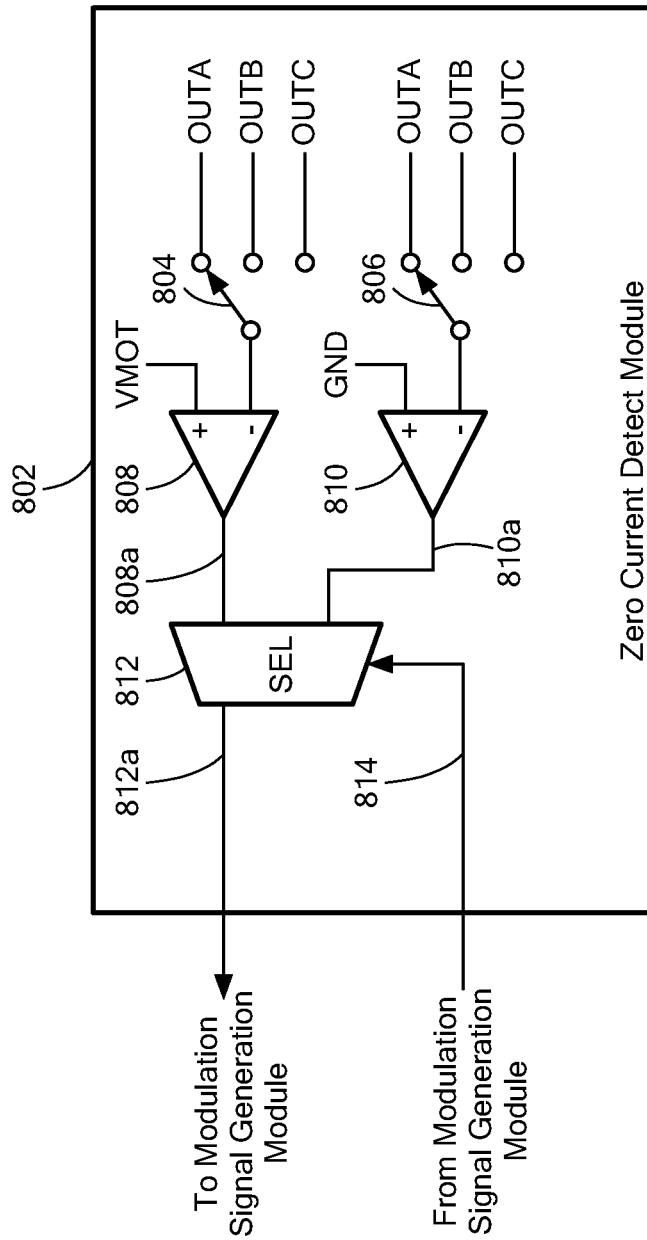


FIG. 8

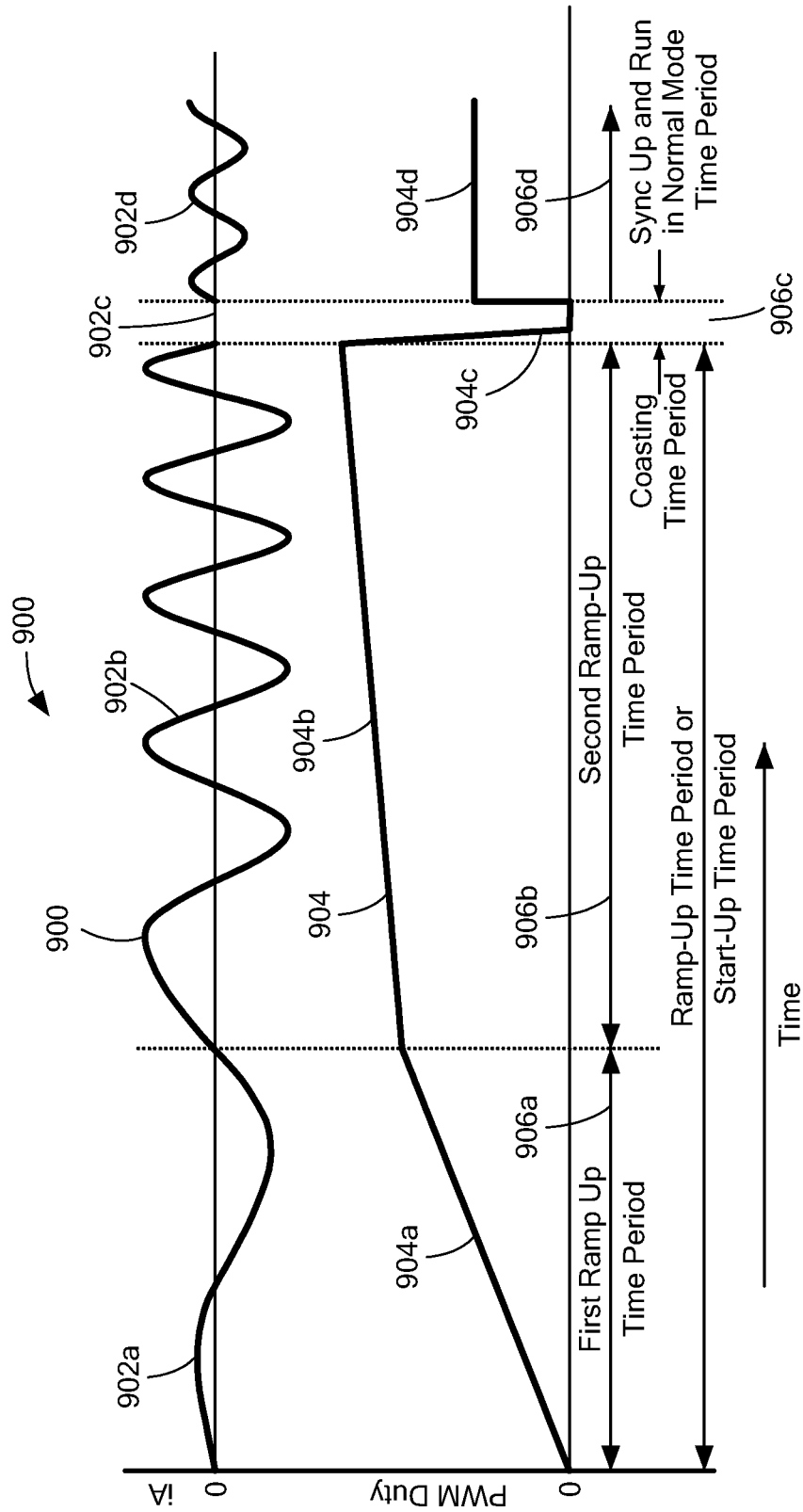


FIG. 9

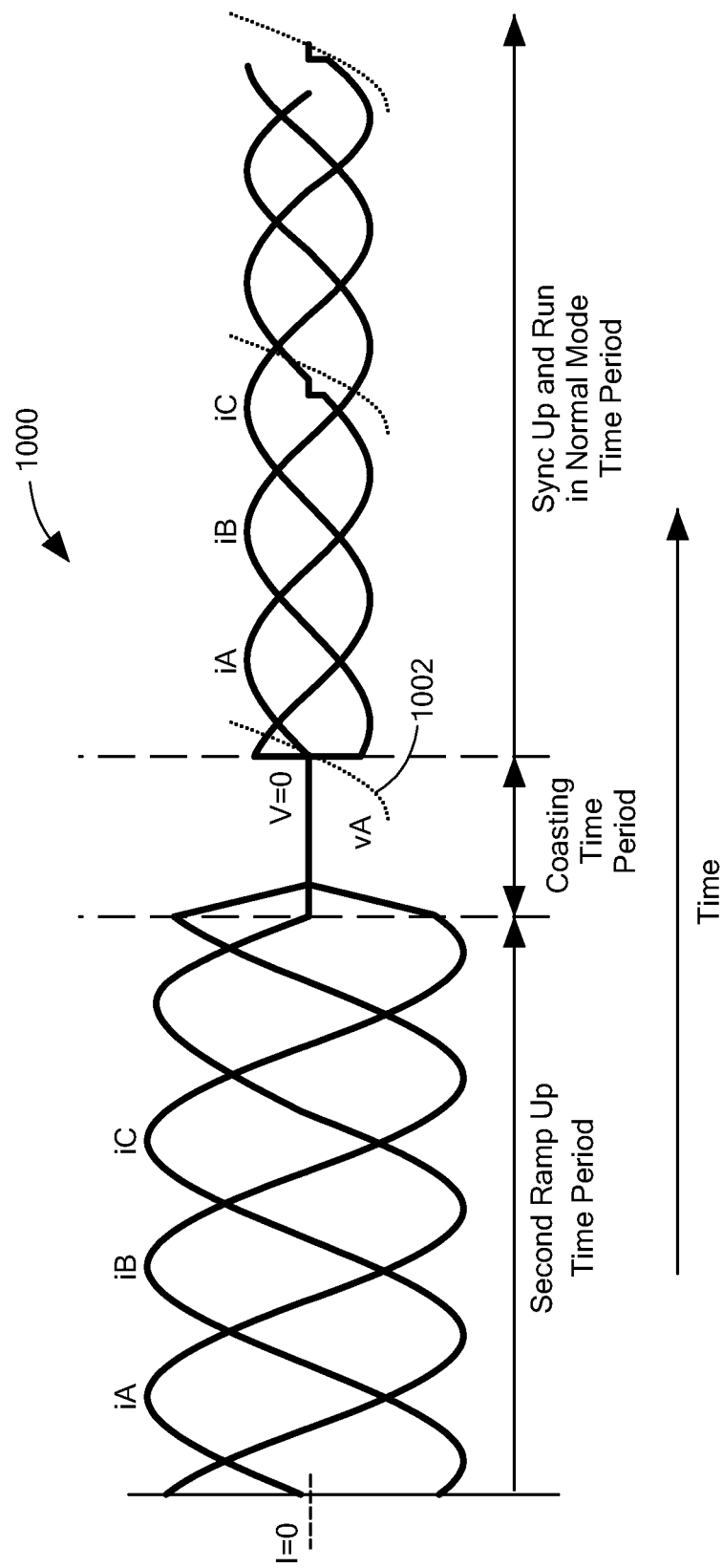


FIG. 10

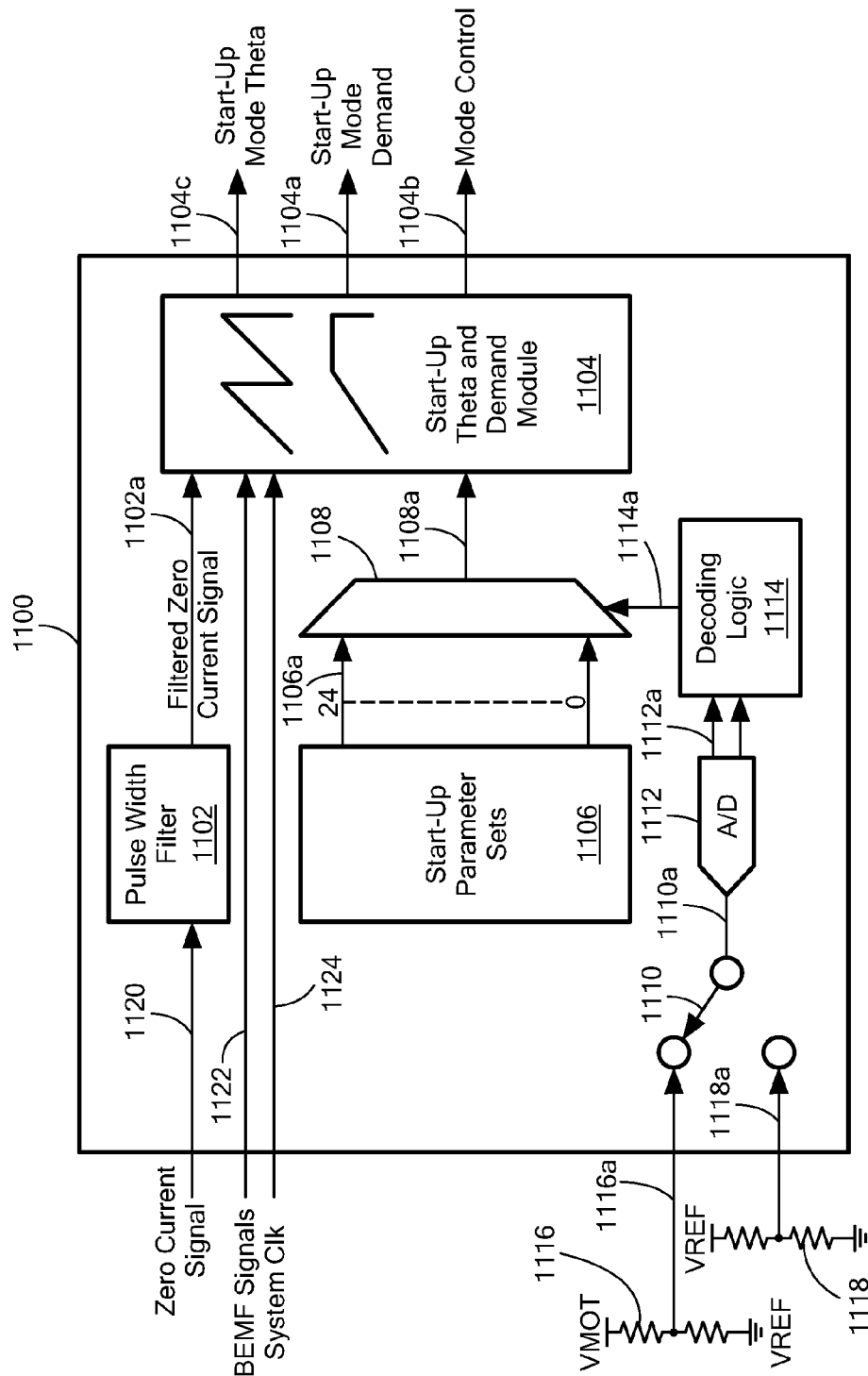


FIG. 11

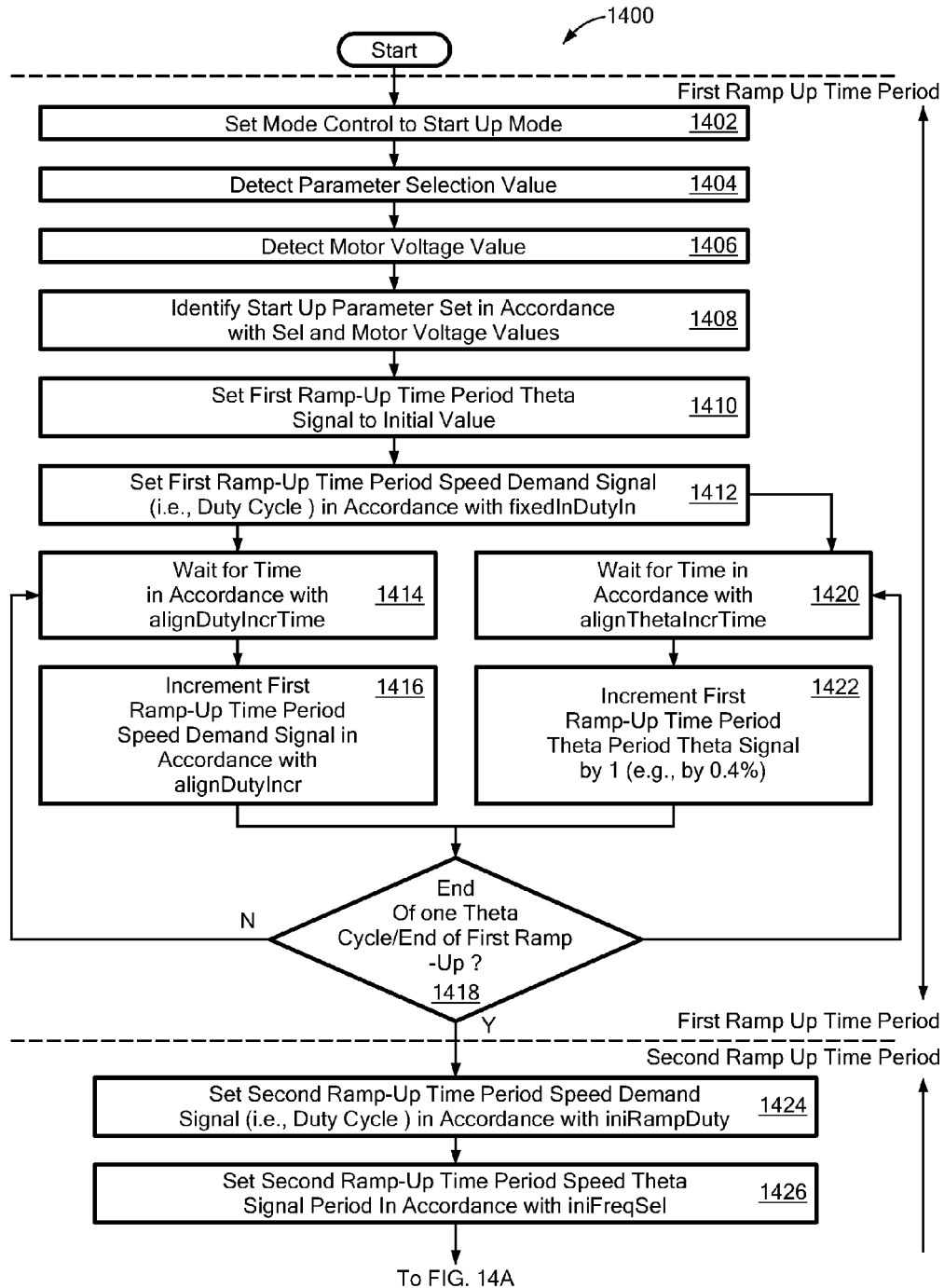
	Bits	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9	Set 10	Set 11	Set 12
fixedIniDutyIn	9	2%	val2a	val3a	val4a	val5a	val6a	val7a	val8a	val9a	val10a	val11a	val12a
alignDutyIncrTime	10	20 ms	val2b	val3b	val4b	val5b	val6b	val7b	val8b	val9b	val10b	val11b	val12b
alignDutyIncr	6	0.2%	val2c	val3c	val4c	val5c	val6c	val7c	val8c	val9c	val10c	val11c	val12c
alignThetaIncrTime	9	2 ms	val2d	val3d	val4d	val5d	val6d	val7d	val8d	val9d	val10d	val11d	val12d
iniRampDuty	9	7%	val2e	val3e	val4e	val5e	val6e	val7e	val8e	val9e	val10e	val11e	val12e
dutyIncr	6	0.40%	val2f	val3f	val4f	val5f	val6f	val7f	val8f	val9f	val10f	val11f	val12f
freqUpdateTime	8	100 ms	val2g	val3g	val4g	val5g	val6g	val7g	val8g	val9g	val10g	val11g	val12g
iniFreqSet	5	2 Hz	val2h	val3h	val4h	val5h	val6h	val7h	val8h	val9h	val10h	val11h	val12h
noOfFreq	5	5	val2i	val3i	val4i	val5i	val6i	val7i	val8i	val9i	val10i	val11i	val12i
iniDutyAfterCoast	9	7%	val2j	val3j	val4j	val5j	val6j	val7j	val8j	val9j	val10j	val11j	val12j

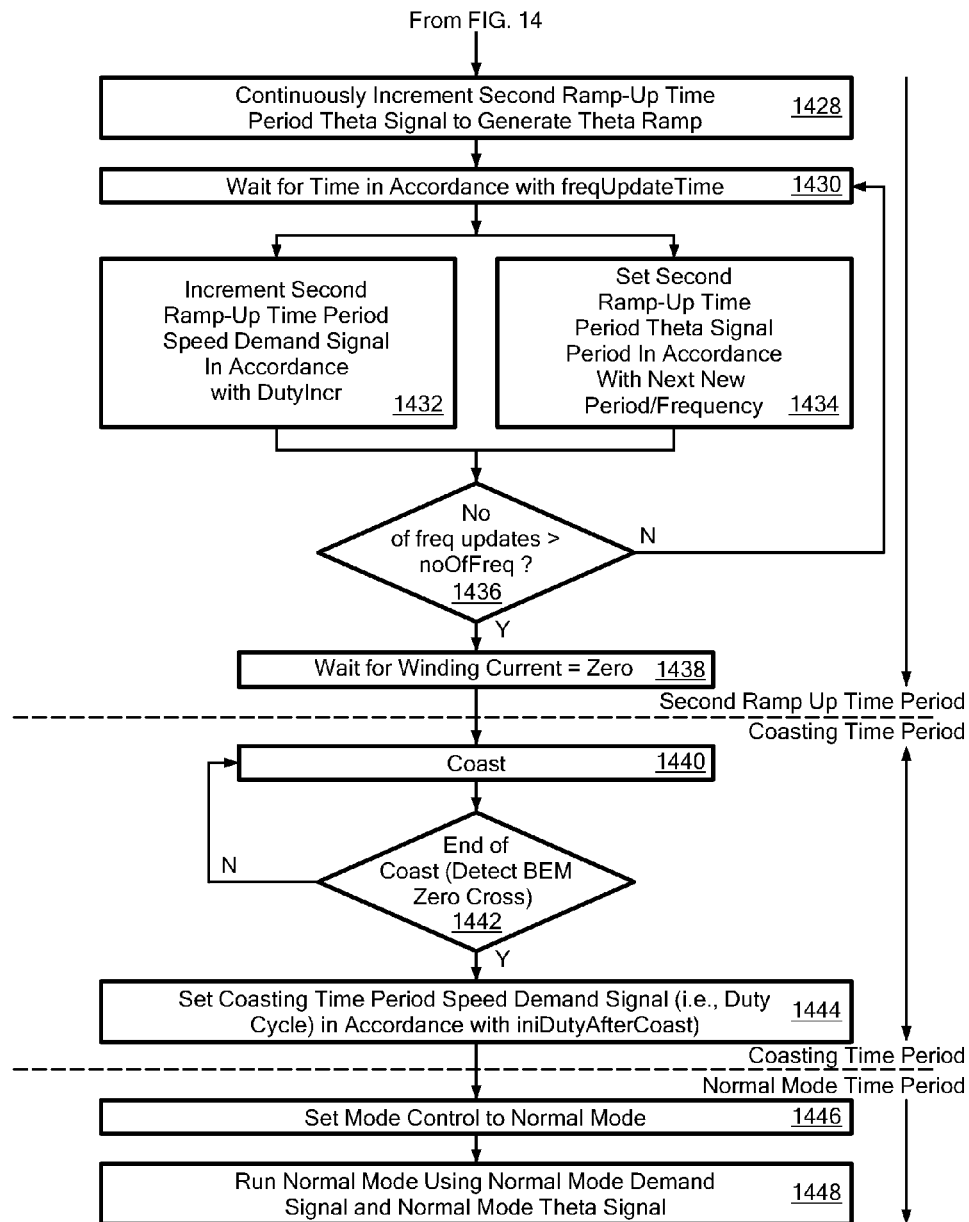
	Bits	Set 13	Set 14	Set 15	Set 16	Set 17	Set 18	Set 19	Set 20	Set 21	Set 22	Set 23	Set 24
fixedIniDutyIn	9	val13a	val14a	val15a	val16a	val17a	val18a	val19a	val20a	val21a	val22a	val23a	val24a
alignDutyIncrTime	10	val13b	val14b	val15b	val16b	val17b	val18b	val19b	val20b	val21b	val22b	val23b	val24b
alignDutyIncr	6	val13c	val14c	val15c	val16c	val17c	val18c	val19c	val20c	val21c	val22c	val23c	val24c
alignThetaIncrTime	9	val13d	val14d	val15d	val16d	val17d	val18d	val19d	val20d	val21d	val22d	val23d	val24d
iniRampDuty	9	val13e	val14e	val15e	val16e	val17e	val18e	val19e	val20e	val21e	val22e	val23e	val24e
dutyIncr	6	val13f	val14f	val15f	val16f	val17f	val18f	val19f	val20f	val21f	val22f	val23f	val24f
freqUpdateTime	8	val13g	val14g	val15g	val16g	val17g	val18g	val19g	val20g	val21g	val22g	val23g	val24g
iniFreqSet	5	val13h	val14h	val15h	val16h	val17h	val18h	val19h	val20h	val21h	val22h	val23h	val24h
noOfFreq	5	val13i	val14i	val15i	val16i	val17i	val18i	val19i	val20i	val21i	val22i	val23i	val24i
iniDutyAfterCoast	9	val13j	val14j	val15j	val16j	val17j	val18j	val19j	val20j	val21j	val22j	val23j	val24j

FIG. 12

Selection Value	Motor Voltage	VMOT < Voltage A	Voltage A ≤ VMOT ≤ Voltage B	VMOT > Voltage B
0		Set 1	Set 1	Set 1
1		Set 2	Set 2	Set 2
2		Set 3	Set 3	Set 3
3		Set 4	Set 4	Set 4
4		Set 5	Set 5	Set 5
5		Set 6	Set 6	Set 6
6		Set 7	Set 7	Set 7
7		Set 8	Set 8	Set 8
8		Set 9	Set 9	Set 9
9		Set 10	Set 10	Set 10
10		Set 11	Set 11	Set 11
11		Set 12	Set 12	Set 12
12		Set 13	Set 14	Set 15
13		Set 16	Set 17	Set 18
14		Set 19	Set 20	Set 21
15		Set 22	Set 23	Set 24

FIG. 13

**FIG. 14**

**FIG. 14A**

1

ELECTRONIC CIRCUIT AND METHOD FOR ADJUSTING START-UP CHARACTERISTICS OF DRIVE SIGNALS APPLIED TO AN ELECTRIC MOTOR

CROSS REFERENCE TO RELATED APPLICATIONS

Not Applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not Applicable.

FIELD OF THE INVENTION

This invention relates generally to electric motor control circuits and, more particularly, to an electric motor control circuit that can adjust start-up drive signal characteristics applied to an electric motor during a start-up mode of operation in accordance with a user input and that can synchronize the start-up mode of operation with a normal mode of operation that occurs thereafter.

BACKGROUND OF THE INVENTION

Circuits to control and drive brushless DC (BLDC) electric motors are known. In some arrangements, the circuits provide a particular a ramp-up of the speed of the electric motor when the electric motor is first powered up. However, such circuits are only able to provide one particular predetermined type of ramp-up.

Some known electric motor drive circuits are described in U.S. Pat. No. 7,590,334, issued Sep. 15, 2009, U.S. Pat. No. 7,747,146, issued Jun. 29, 2010, U.S. patent application Ser. No. 13/271,723, filed Oct. 12, 2011, U.S. patent application Ser. No. 13/599,225, filed Aug. 30, 2012, and U.S. patent application Ser. No. 13/599,234, filed Aug. 30, 2012, all of which are incorporated herein by reference in their entireties and assigned to the assignee of the present invention.

A BLDC electric motor can be used in different applications. For example, the same BLDC electric motor can be used with different fan blade arrangements in different applications. Different types of BLDC electric motors can also exhibit different load behaviors versus speed.

Motor noise, vibration, and efficiency are influenced by a variety of characteristics.

For sensor-less motor drive arrangements (i.e., motor drivers that do not rely upon Hall Effect elements to sense position of the motor shaft), reliable start-up is an important part of the design. Some sensor-less motor drive arrangements rely upon so-called "back EMF," or simply "BEMF" generated on the motor windings to sense a position of a motor shaft. In order to sense the BEMF, the electric motor must be spinning at some minimum speed and drive signals to the electric motor must generally be turned off, and thus, BEMF is not conventionally used to sense motor position at the very beginning of a start-up of a motor.

Various methods have been used to start an electric motor. For example, a so-called "Trap Drive" arrangement has been used, in which motor windings of an electric motor are driven with trapezoidal (trap) drive signals through six states at a predetermined fixed rate during start-up. During start-up, in some embodiments, start-up motor current is controlled by pulse width modulation (PWM) of the trap drive signals, and in other embodiments, start-up motor current is controlled by current limiting of the trap drive signals. BEMF is checked

2

during the start-up process and the commutation of the phases of the trap drive signals are synchronized with BEMF zero crossings.

After the electric motor is started with the above-described trap drive signals, in some embodiments, the motor control electronics continues to run the electronic motor with trap drive signals in a normal mode of operation.

One of the drawbacks of using the trap drive signals during start-up and/or during the normal mode of operation after start-up, is that the trap drive signals result in is audible noise from the electric motor due to vibrations. Even when the trap drive signals are used as an envelope for PWM drive signals with very low duty cycles and current levels, the noise can still be very prominent. For many applications, the noise is not acceptable.

Sine drives that result in sinusoidal currents in the motor windings are known. Sine drives are quieter than trap drives.

As described above, the BEMF signals are not available until the electric motor has achieved some minimum rotating speed. Thus, during start-up of the electric motor, a common method ramps up the motor slowly, without BEMF motor position information, and using a fixed and predetermined ramp-up rate and technique. However, different electric motors (e.g., motors with different inertial masses and coupled loads) require different motor drive signal start-up profiles.

A motor controller integrated circuit has only a limited number of pins. A motor controller integrated circuit must also be built for a low cost.

It would be desirable to provide a motor controller electronic circuit (either integrated or non-integrated) that uses a small number of pins, that is low cost (e.g., small silicon surface area), that can generate sine drive signals instead of trap drive signals for low noise, that can be used to drive a wide variety of types of electric motors, while providing a proper sine drive start-up profile synchronized with a sine drive normal mode of operation for each type of electric motor.

SUMMARY OF THE INVENTION

The present invention provides a motor controller electronic circuit (either integrated or non-integrated) that uses a small number of pins, that is low cost (e.g., small silicon surface area), that can generate sine drive signals instead of trap drive signals for low noise, that can be used to drive a wide variety of types of electric motors, while providing a proper sine drive start-up profile synchronized with a sine drive normal mode of operation for each type of electric motor.

In accordance with one aspect of the present invention, a method of driving, with a motor control circuit, a multi-phase motor having a plurality of motor windings, includes receiving, from outside of the motor control circuit, a selection signal. The method also includes identifying, with the motor control circuit, a set of parameter values from among a plurality of sets of parameter values retained on the motor control circuit, the identifying done in accordance with the selection signal. The method also includes determining, in accordance with the identified set of parameter values, with the motor control circuit, start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings, wherein the determined start-up signal characteristics of the plurality of drive signals comprise a ramped start-up of the electric motor during a ramp-up time period during a start-up mode of operation. The method also includes generating, with the motor control circuit, the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning.

3

In accordance with another aspect of the present invention, a motor control circuit for driving a multi-phase motor having a plurality of motor windings includes a motor control circuit. The motor control circuit includes a start-up control module configured to: receive, from outside of the motor control circuit, a selection signal; identify set of parameter values from among a plurality of sets of parameter values retained on the motor control circuit, the identifying done in accordance with the selection signal; and determine, in accordance with the identified set of parameter values, start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings. The determined start-up signal characteristics of the plurality of drive signals comprise a ramped start-up of the electric motor during a ramp-up time period during a start-up mode of operation. The motor control circuit is configured to generate the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of the invention, as well as the invention itself may be more fully understood from the following detailed description of the drawings, in which:

FIG. 1 is a block diagram of an exemplary motor control circuit having a modulation signal generation module, a current measurement module, a position measure module, and a start-up control module;

FIG. 2 is a graph showing a variety of waveforms associated with the exemplary motor control circuit of FIG. 1, in particular, when the motor control circuit is used to provide a sinusoidal drive to a motor;

FIG. 3 is another graph showing a variety of waveforms associated with exemplary motor control circuit of FIG. 1, in particular, when the motor control circuit is used to provide a sinusoidal drive to the motor, and showing phase differences between a current signal and a position reference signal;

FIG. 4 is a block diagram of an exemplary modulation signal generation module that can be used as a modulation signal generation module of the exemplary motor control circuit of FIG. 1;

FIGS. 5 and 5A are block diagrams showing exemplary half bridge output stages of the exemplary motor control circuit of FIG. 1, and showing directions of motor winding current at different phases of operation;

FIG. 6 is a graph showing waveforms associated with the motor winding, in particular, a sinusoidal current, a modulation waveform associated with a sinusoidal drive of the motor winding, and a pulse width modulated (PWM) signal that drives a motor in accordance with the modulation waveform;

FIG. 7 is a pictorial showing details of positive and negative states of the PWM signal of FIG. 6;

FIG. 7A is a graph showing a PWM drive signal applied to an electric motor, and showing a sinusoidal current associated with the PWM drive signal;

FIG. 8 is a block diagram of an exemplary current measurement module that can be used as the current measurement module of FIG. 1;

FIG. 9 is a graph showing characteristics of a start-up mode demand signal and characteristics of current in one of the motor windings in accordance with a first ramp-up time period, second ramp-up time period, coasting time period, and a normal mode time period, wherein the first and second ramp-up time periods together correspond to a start-up time period and to a start-up mode of operation;

FIG. 10 is another graph showing characteristics of three currents corresponding to three motor windings in the second ramp-up time period, in the coasting time period, and in the normal mode time period;

FIG. 11 is a block diagram of an exemplary start-up control module that can be used as a start-up control module of FIG.

4

1, the start-up control module having retained therein a plurality of sets of start-up parameter values;

FIG. 12 is a table showing exemplary sets of start-up parameter values that can be used as the sets of start-up parameter values of FIG. 11;

FIG. 13 is a table showing a particular logic that can be used to combine a selection value provided by a user with a motor voltage in order to select which one of the plurality of sets of parameter values to use during the start-up time period; and

FIGS. 14 and 14A together form a flowchart showing a process that can be used by the start-up control module of FIG. 1 in order to start a motor rotating.

DETAILED DESCRIPTION OF THE INVENTION

Before describing the present invention, some introductory concepts and terminology are explained. As used herein, the term "modulation waveform" is used to describe an envelope (i.e., a modulation envelope) or characteristic function of another signal, for example, a pulse width modulated (PWM) signal.

An exemplary normal mode of operation of a motor control circuit is generally described herein. During the normal mode of operation, the motor control circuit generates normal mode motor drive signals to cause an electric motor to continue rotating once it has been started. Further details of the exemplary normal mode of operation can be found in U.S. patent application Ser. No. 13/599,225, filed Aug. 30, 2012, and U.S. patent application Ser. No. 13/599,234, filed Aug. 30, 2012.

A start-up mode of operation, which precedes the normal mode of operation, is also described herein. During the start-up mode of operation, the motor control circuit generates start-up mode motor drive signals to cause an electric motor to begin rotating from zero speed.

A synchronization of motor drive signals between the start-up mode of operation and the normal mode of operation is also described herein.

While a particular normal mode of operation is described herein, it should be understood that the start-up mode of operation described herein can be followed by any type of normal mode of operation. It should also be understood that the synchronization techniques described herein can apply to other types of normal modes of operation.

Referring to FIG. 1, an exemplary motor control circuit 102 is coupled to drive an electric motor 104.

The motor 104 is shown to include three windings 104a, 104b, 104c, which are each often depicted as a respective equivalent circuit having an inductor in series with a resistor and in series with a back EMF voltage source. For example, the winding A 104a is shown to include an inductor 130 in series with a resistor 131 and in series with a back EMF voltage source VA 136. The voltage of the back EMF voltage source VA 136 is not directly observable when a current is flowing in an associated motor winding, but it directly observable when the current through the associated winding is zero.

In general, the voltage across a motor winding, for example, across the winding A 104a, is governed by the following equation:

$$V_{outA} - V_{common} = VA + IR + L \frac{dI}{dt},$$

where:

V_{outA}=observable voltage at one end of the winding A;

V_{common}=voltage at junction of the windings 104a, 104b, 104c;

R=resistance of the resistor 131;

L=inductance of inductor 130;

I=current through winding; and

VA=back EMF voltage

Thus, it can be seen that, if the current through the winding 104a is zero, then V_{outA}=VA, which is an observable voltage.

The motor control circuit **102** can include nodes **102a-102h**. In some embodiments, each one of the nodes **102a-102h** corresponds to a respective integrated circuit pin.

The motor control circuit **102** can include a start-up control module **148**. The start-up control module **148** can be coupled to receive a selection signal **152a** from outside of the motor control circuit **102**. In some embodiments, the selection signal **152a** is generated by a resistor divider **152** provided by a user. The voltage divider **152** can be coupled to receive a reference voltage, VREF, which, in some embodiments, can be provided by the motor control circuit **102** at the node **102f**. However, in other embodiments, the voltage divider **152** can be coupled to receive another voltage, for example, a voltage provided from outside of the motor control circuit **102**.

In other embodiments, the selection signal **152a** can be provided by other means and can have other characteristics. For example, in some other embodiments, the selection signal **152a** can be provided from an amplifier outside of the motor control circuit **102**. In some other embodiments, the selection signal **152a** is a binary signal, for example, a PWM signal or a digital signal having information therein.

In some embodiments, the start-up control module **148** can also be coupled to receive a voltage signal **154a** generated by a voltage divider **154**. The voltage divider **154** can be coupled to receive the motor voltage, VMOT, and, therefore, the voltage signal **154a** is representative of the motor voltage.

The start-up control module **148** is also coupled to receive one or more back EMF signals **150** from a respective one or more of the nodes **102b, 102c, 102d**.

The start-up control module **148** is also coupled to receive a detected zero current signal **144a** indicative of a zero current passing through the motor winding. Function of the detected zero current signal **144a** is described more fully below in conjunction with FIGS. **8** and **9**.

The start-up control module **148** can be configured to generate a start-up mode demand signal **148a**, a start-up mode theta signal **148c**, and a mode control signal **148b**.

The start-up control module **148** is configured to provide the mode control signal **148b** having at least two states. A first state of the mode control signal **148b** results in the motor control circuit **102** performing the above-described start-up mode of operation, and a second different state of the mode control signal **148b** results in the motor control circuit **102** performing the above-described normal mode of operation.

Further details of the start-up control module **148** are described below in conjunction with FIG. **11**. However, let it suffice here to say that, during the start-up mode of operation, the motor control circuit **102** uses the start-up mode demand signal **148a** and the start-up mode theta signal **148c**, but uses other similar signals during the normal mode of operation.

The motor control circuit **102** includes a speed demand generator **107** coupled to receive an external speed demand signal **106** at the node **102h** from outside of the motor control circuit **102**. The external speed demand signal **106** can be in one of a variety of formats. In general the external speed demand signal **106** is indicative of a speed of the motor **104** that is requested from outside of the motor control circuit **102**. The external speed demand signal **106** is used in the normal mode of operation.

The speed demand generator **107** is configured to generate a normal mode demand signal **107a**. A 2:1 switch **156** is coupled to receive the normal mode demand signal **107a** and also the start-up mode demand signal **148a**. The 2:1 switch **156** is also coupled to receive the mode control signal **148b**. A normal mode state of the mode control signal **148b** causes the 2:1 switch **156** to pass the normal mode demand signal **107a** through the 2:1 switch **156** as a selected demand signal **156a**,

while a start-up mode state of the mode control signal **148b** causes the 2:1 switch **156** to pass the start-up mode demand signal **148a** through the 2:1 switch **156** as the selected demand signal **156a**.

The selected demand signal **156** is received by a pulse width modulation (PWM) generator **108**. The PWM generator **108** is configured to generate PWM signals **108a**, a maximum duty cycle of which is controlled by the selected demand signal **156a**, i.e., by the normal mode demand signal **107a** during the normal mode of operation, or by the start-up mode demand signal **148a** during the start-up mode of operation.

The PWM generator **108** is also coupled to receive modulation waveforms **146a, 146b, 146c** from a modulation signal generation module **146**. The PWM signals **108a** are generated with a modulation characteristic (i.e., a relative time-varying duty cycle) in accordance with the modulation waveforms **146a, 146b, 146c**. Modulation waveforms and associated PWM signals are described more fully below in conjunction with FIG. **6**. It will become apparent from discussion below that the modulation waveforms in the normal mode of operation have different characteristics than modulation waveforms in the start-up mode of operation.

The modulation signal generation module **146** is also coupled to receive the mode control signal **148b** and the start-up mode theta signal **148c**, which are described more fully below.

The motor control circuit **102** also includes a gate driver circuit **110** coupled to receive the PWM signals **108a** and configured to generate PWM gate drive signals **110a, 110b, 110c, 110d, 110e, 110f** to drive six transistors **112, 114, 116, 118, 120, 122** arranged as three half bridge circuits **112/114, 116/118, 120/122**. The six transistors **112, 114, 116, 118, 120, 122** operate in saturation to provide three motor drive signals VoutA, VoutB, VoutC, **124, 126, 128**, respectively, at the nodes **102d, 102c, 102b**, respectively.

The motor control circuit **102** can also include a position measurement module **142**, which can be coupled to receive back EMF signal(s) (e.g., can be coupled to one or more of the nodes **102b, 102c, 102d**, at which include back EMF signals are directly observable at times when the motor windings **104a, 104b, 104c** are not being driven by the motor drive signals **124, 126, 128**, and respective winding currents are zero). The position measure module **142** is configured to generate a position reference signal **142a** indicative of a rotational reference position of the motor **104**.

The motor control circuit **102** can also include a current measurement module **144**, which can be coupled to receive one of the motor drive signals **124, 126, 128**. The current measurement module **144** is configured to generate a zero current signal **144a** indicative of a zero crossing of the current in one or more of the motor windings. An exemplary current measurement module is described in further detail below in conjunction with FIG. **8**.

The modulation signal generation module **146** is coupled to receive the position reference signal **142a** and the zero current signal **144a**. During the normal mode of operation, the modulation signal generation module **146** is configured to generate the modulation waveforms **146a, 146b, 146c** having phases in accordance with a phase difference between the position reference signal **142a** and the zero current signal **144a**. An exemplary modulation signal generation module **146** is described below in conjunction with FIG. **4**.

In contrast, during the start-up mode of operation, the modulation signal generation module **146** is configured to generate the modulation waveforms **146a, 146b, 146c** under control of the start-up mode theta signal **148c**.

The motor control circuit **102** can be coupled to receive the motor voltage **VMOT**, or simply **VM**, at the node **102a**, which is supplied to the motor through the transistors **112**, **116**, **120** during times when the upper transistors **112**, **116**, **120** are turned on. It will be understood that there can be a small voltage drop (for example, 0.1 volts) through the transistors **112**, **116**, **120** when they are turned on and supplying current to the motor **104**.

As described above, during the normal mode of operation, the motor control circuit **102** can automatically adjust a timing, i.e., a phase, of the drive signals **124**, **126**, **128** in relation to a sensed rotational position of the motor **104**.

From the above, it should be understood that, during the start-up mode of operation, the motor control circuit **102** operates using the start-up mode demand signal **148a** and the start-up mode theta signal **148c**. During the normal mode of operation, the motor control circuit operates using the normal mode demand signal **107a** and using a theta signal generated within the modulation signal generation module **146** and described more fully below in conjunction with FIG. 4.

In general, the selected demand signal **156a** applied to the PWM generator **108** is most closely associated with an amplitude of the motor drive signals **124**, **126**, **128** applied to the motor **104**. In contrast, frequencies, i.e. rates, of the modulation waveforms **146a**, **146b**, **146c** are most closely associated with frequencies of the motor drive signals **124**, **126**, **128** applied to the motor. Both amplitude and frequency of the drive signals **124**, **126**, **128** influence a rotation speed of the motor **104**.

It will also be understood that the selection signal **152a** requires only one pin on the motor control circuit **102**.

Referring now to FIG. 2, graphs **200**, **240**, and **260** have a horizontal axes with scales in units of time in arbitrary units. The graphs **200**, **220**, **240** have vertical axes with scales in units of voltage in arbitrary units. The graph **260** has a vertical axis with a scale in units of current in arbitrary units.

A signal **202** is representative of a back EMF signal (i.e., a voltage signal) on one of the motor windings (e.g., winding **A 104a**) of the motor **104** of FIG. 1 when the motor **104** is spinning. The back EMF voltage **202** is generally sinusoidal. It will be understood that the back EMF signal **202** is only fully observable on a motor winding when the motor winding is not being driven by one of the drive signals **124**, **126**, **128** of FIG. 1.

In some embodiments of the motor control circuit **102** of FIG. 1, the zero crossing of the back EMF signal **202** can be used by the position measurement module **142** to identify a reference rotational position of the motor **104**. Particularly during the normal mode of operation, it is desirable that the zero crossing of the back EMF signal **202** at a time **208** be coincident or nearly coincident with a zero current passing through the motor winding upon which the back EMF signal **202** is generated. Such a relationship will result in most efficient motor operation.

Signals **242**, **244**, **246** are generally representative of the above-described modulation waveforms **146a**, **146b**, **146c** of FIG. 1 during both the normal mode and the start-up mode of operation. The modulation waveforms **242**, **244**, **246** are representative of modulation envelopes used to generate PWM signals to drive the motor **104**. Correspondence between the modulation waveforms **242**, **244**, **246** and the PWM signals is described more fully below in conjunction with FIG. 6.

It will be recognized that the modulation waveform **242** is associated with the winding **A 104a** of FIG. 1 and generally aligns with the back EMF signal **202** that is associated with the same winding. The other modulation waveforms **244**, **246**

are associated with the other windings **B**, **C 104b**, **104c**, respectively, of the motor **104** of FIG. 1.

Signals **262**, **264**, **266** are representative of currents that appear on the windings **A**, **B**, **C 104a**, **104b**, **104c**, respectively, of the motor **104** of FIG. 1 during the normal mode and the start-up mode of operation. It will be understood that the actual current signals on the motor windings may be more complex than those shown in the signals **262**, **264**, **266**. However the current signals **262**, **264**, **266** are representative of an average current versus time through the three motor windings. It will be understood that the current **262** on the motor winding **A 104a** is generally in phase with the back EMF signal **202**. However, there can be a phase difference between the current signal **262** and the associated back EMF signal **202** as described more fully below in conjunction with FIG. 3.

An electrical revolution of the motor **104** can be divided into six states, or time periods, **201a**, **201b**, **201c**, **201d**, **201e**, **201f**.

Referring now to FIG. 3, a graph **300** has a horizontal axis with a scale in units of time in arbitrary units. The graph **300** also has a vertical axis with a scale in units of voltage and current in arbitrary units. A graph **320** has a horizontal axis with a scale in units of time in arbitrary units. The graph **320** also includes a vertical axis with a scale in units of voltage in arbitrary units.

The graphs **300** and **320** are used to indicate phase adjustments that are performed during the exemplary normal mode of operation. However, other normal modes of operation, including normal modes of operation in which phase is not adjusted are also possible.

A signal **304** is representative of a current signal on the winding **A 104a** of FIG. 1. Thus, the signal **304** corresponds to the signal **262** of FIG. 2. A signal **302** is representative of a back EMF signal **136** on the winding **A 104a** of FIG. 1. Thus, the signal **302** corresponds to the signal **202** of FIG. 2. Zero crossings of the signals **302**, **304** will be apparent. A time difference **308** is indicative of a time difference between a zero crossing of the back EMF signal **302** and a zero crossing of the current signal **304**. Therefore, the time difference **308** is representative of a time difference between a rotational position reference (i.e., the zero crossing of the back EMF signal **302**) and a zero current passing through the associated motor winding.

A signal **306** is representative of a current signal on the winding **A 104a** of FIG. 1 during a time period during which the motor **104** is accelerating in rotational speed or during which the motor **104** is rotating at high speed. It can be seen that relative phases have shifted. The zero crossing of the current signal **306** is retarded with respect to the zero crossing of the back EMF signal **302**. The zero crossing of the back EMF signal **302** is indicative of a reference rotational position of the motor **104**. The zero crossing of the current signal **306** is representative of a zero current through the motor winding **A 104a**. It is desirable that the zero crossings coincide in time and phase. A lack of time coincidence will result in increased motor noise and vibration, and decreased motor efficiency.

A modulation waveform **322** is the same as or similar to the modulation waveform **242** of FIG. 2. Thus, when the motor is accelerating or rotating rapidly, it can be seen that the current signal **306** is retarded relative to the modulation waveform **322**. It would be desirable to advance the modulation waveform **322** (i.e., move the modulation waveform **322** to the left) to advance the current signal **306** so that a zero crossings of the current signal **306** can occur coincident or nearly coincident with the zero crossing of the back EMF signal **302**, which is indicative of a rotational reference position of the motor **104**.

In general, in the exemplary normal mode of operation, the modulation signal generation module **146** of FIG. **1** is able to advance or retard the various modulation waveforms **146a**, **146b**, **146c** in accordance with a received rotational position reference signal **142a** and in accordance with the zero current signal **144a**, of which the back EMF signal **302** and the current signals **304**, **306** are representative.

For conventional sinusoidal motor drive signals, such as those described above in conjunction with FIGS. **2** and **3**, for reasons described above in conjunction with FIG. **1**, it is not readily possible to observe and detect a zero crossing of the back EMF signal **302**, because each one of the motor windings **104a**, **104b**, **104c** is constantly being driven. In order to observe a back EMF signal, it is necessary to at least momentarily stop a drive signal to a motor winding. Thus, with a sinusoidal motor drive signal arrangement, in some embodiments, the sinusoidal drive signal to at least one of the windings **104a**, **104b**, **104c** of the motor **104** can be stopped for a small time window in order to observe the zero crossing of the back EMF signal. To this end, in the motor control circuit **102** of FIG. **1**, a control signal **142b** used in the normal mode of operation can be provided by the position measurement module **142** to the gate driver **110**. Other means of stopping the drives signals described below are used during the start-up mode of operation.

Referring now to FIG. **4**, a modulation signal generation module **402** can be used as the modulation signal generation module **146** of FIG. **1**.

The modulation signal generation module **402** is coupled to receive a detected position reference signal **414** and a detected zero current signal **418**. The detected position reference signal **414** can be the same as or similar to the position reference signal **142a** of FIG. **1**. The detected zero current signal **418** can be the same as or similar to the zero current signal **144a** of FIG. **1**.

As described above, the detected position reference signal **414** can be generated in conjunction with zero crossings of a back EMF signal using a sinusoidal drive waveform by using a short time period during which the sinusoidal drive to a winding is stopped.

The modulation signal generation module **402** is also coupled to receive a system clock signal **416** having a fixed high frequency.

A so-called "theta ramp generator" **404**, used in the exemplary normal mode of operation, is coupled to receive the detected position reference signal **414** and the system clock signal **416**. The theta ramp generator **404** is configured to generate an unadjusted theta signal **404a**, which can be a digital signal comprised of a sequence of values representative of a ramp signal that periodically reaches a terminal value and resets to zero. The reset time of the ramp signal is fixed in relation to the position reference (i.e., a fixed rotational position of the motor **104**) of which the detected position reference signal **414** is indicative.

In operation, the theta ramp generator **404** can identify a time period, measured by counting a number of system clock transitions, between position references identified by the detected position reference signal **414**. In other words, the theta ramp generator **404** can identify a time (i.e., a number of transitions of the system clock signal **416**) that it takes the motor **104** to turn through one electrical rotation. The theta ramp generator **404** can divide the identified number of transitions of the system clock **416** by a fixed scalar, for example, by **256**. Thus, a motor electrical revolution can be divided into **256** parts. Accordingly, the clock signal **402** can have a frequency that achieves, for example, **256** transitions during one electrical revolution of the motor. The clock signal **402** can be

generated by and used by the theta ramp generator **404** to generate a rate at which ramp values of the unadjusted theta signal **404a** are incremented and output within the unadjusted theta signal **404a**. Thus, it will be understood that resets to zero of the ramp signal in the unadjusted theta signal **404a** are achieved once for every electrical revolution of the motor, and there can be, for example, **256** steps in the ramp.

A timing/phase error detector **410**, used in the exemplary normal mode of operation, is coupled to receive the detected zero current signal **418**, coupled to receive the detected position reference signal **414**, and coupled to receive the clock signal **402**.

During the exemplary normal mode of operation, the timing/phase error detector **410** is configured to identify a time difference (i.e., a phase difference) between a position reference identified by the detected position reference signal **414** and a zero current crossing identified by the detected zero current signal **418**.

Referring briefly again to FIG. **3**, in other words, the timing/phase error detector **410** is operable to identify a time difference between the zero crossing of the current signal **304** or **306** and a zero crossing of a back EMF voltage signal **302**.

Referring again to FIG. **4**, the timing/phase error detector **410** is configured to generate an error signal **410a**, which, in some embodiments, can be a digital value, representative of the identified time (i.e., phase) difference.

A proportional integrator differentiator (PID), or, in other embodiments, a proportion integrator (PI), can be coupled to receive the error signal **410a**, and configured to essentially filter the error signal **410a** to generate an adjustment signal **412a**. In some embodiments, the adjustment signal **412a** can be a digital value proportional to the time difference identified by the timing/phase error detector **410**.

A summing module **406** is coupled to receive the unadjusted theta signal **404a** (i.e., a sequential set of digital values representative of a resetting ramp signal at a fixed phase), coupled to receive the adjustment signal **412a**, and configured to generate a normal mode theta signal **406a**.

The modulation signal generation module **402** can also be coupled to receive a start-up mode theta signal **424** and a mode control signal **422**. The start-up mode theta signal **424** can be the same as or similar to the start-up mode theta signal **148c** of FIG. **1**, and the mode control signal **422** can be the same as or similar to the mode control signal **148b** of FIG. **1**.

A 2:1 switch **420** can be coupled to receive the normal mode theta signal **406a** and the start-up mode theta signal **424**. A state of the mode control signal **422** determines which one of the input signals to the 2:1 switch **420** becomes a selected theta signal **420a**.

As described above, the normal mode theta signal **406a** is used in the normal mode of operation, and the start-up mode theta signal **424** is used during the start-up mode of operation.

In the normal mode of operation, it should be understood that the selected theta signal **420a** (i.e., the normal mode theta signal **406a**) is a resetting ramp signal like the unadjusted theta signal **404a**, but for which the reset times of the ramp signal are moved in time, i.e., adjusted phase, in accordance with a value of the adjustment signal **412a**. In the start-up mode of operation, it should be understood that the selected theta signal **420a** (i.e., the start-up mode theta signal **424**) is also resetting ramp signal, a reset rate of which is controlled by the start-up control module **148** of FIG. **1**, and the adjustment signal **412a** is not used.

A modulation profile look up table and processor **408** is coupled to receive the selected theta signal **420a**. The modulation profile look up table and processor **408** is configured to

11

store therein values representative of one or more modulation profiles, for example, the modulation profile **242** of FIG. 2.

In operation, the selected theta signal **420a** (i.e., either the normal mode theta signal **406a** or the start-up mode theta signal **424**) is used to sequence between values of the stored modulation signal within the modulation profile look up table and processor **408**.

It will be understood that, in the normal mode of operation, a phase of the selected theta signal **420a**, of which reset portions of the normal mode theta signal **406a** are representative, is adjustable according to a time difference between a position reference identified within the detected position reference signal **414** and a zero crossing of the current in a motor winding as identified within the detected zero crossing signal **418**. Accordingly, a phase, i.e., a timing of, a modulation signal **408a** generated by the modulation profile look up table and processor **408** is adjustable.

In the start-up mode of operation, the phase adjustment may not be performed. However, in other embodiments, similar circuits can be used to also perform the phase adjustment during the start-up mode of operation.

A processor portion of the modulation profile look up table and processor **408** can automatically generate other modulation profiles **408b**, **408c** at other fixed phases, for example, the modulation profiles **244**, **246** of FIG. 2, which can be at fixed phases relative to the modulation profile **408a**, e.g., the modulation profile **242** of FIG. 2.

Exemplary circuits and methods to detect a zero current through motor windings are described below in conjunction with FIGS. 5-8. However, it should be appreciated that other methods can be used to detect a zero current passing through a motor winding.

Discussion below in conjunction with FIGS. 5, 5A, 6, 7 and 7A applies to both the exemplary normal mode of operation and to the start-up mode of operation. FIGS. 5, 5A, 6, 7, and 7A are used to describe exemplary means by which the current measure module **144** of FIG. 1 can detect a zero current in a motor winding. However, in other embodiments, other techniques can be used to detect zero current.

Referring now to FIG. 5, three half bridge circuits **502**, **504**, **506** correspond to the three half bridge circuits **112/114**, **116/118**, **120/122** of FIG. 1 and are shown driving three motor windings. Currents through the half bridge circuit **502** and through one of the motor windings are indicated by dashed lines identified by circled numbers 1, 2, and 3. The currents 1, 2, and 3 are indicative of currents at different times through the half bridge circuit **502** during a positive polarity of a current signal in the motor winding, e.g., during positive parts of the current signal **262** of FIG. 2. The current 1 is indicative of the upper FET being on, the current 3 is indicative of the lower FET being on, and the current 2 is indicative of both FETs being turned off. It will be appreciated that the current 2 passes through an intrinsic diode of the lower FET, and thus, the voltage VoutA (see e.g., signal **124** of FIG. 1) achieves a voltage approximately 0.7 volts below ground beginning when the two FETs of the half bridge **502** are turned off and returns to ground voltage when the lower FET turns on. Thus, it will be appreciated that, by detecting the voltage VoutA going below ground and returning to ground, an actual zero current through the half bridge **502** and through the associated motor winding can be identified.

Referring now to FIG. 5A, in which like elements of FIG. 5 are shown having like reference designations, currents through the half bridge circuit **502** and through one of the motor windings are again indicated by dashed lines identified by circled numbers 1, 2, and 3. The currents 1, 2, and 3 are indicative of currents at different times through the half

12

bridge circuit **502** during a negative polarity of a current signal in the motor winding, e.g., during negative parts of the current signal **262** of FIG. 2. The current 1 is indicative of the upper FET being on, the current 3 is indicative of the lower FET being on, and the current 2 is indicative of both FETs being turned off. It will be appreciated that the current 2 passes through an intrinsic diode of the upper FET, and thus, the voltage VoutA achieves a voltage approximately 0.7 volts above the voltage VM beginning when the two FETs of the half bridge **502** are turned off and returns to the voltage VM when the upper FET turns on. Thus, it will be appreciated that, by detecting the voltage VoutA going above the voltage VM and returning to the voltage VM, an actual zero current through the half bridge **502** and through the associated motor winding can be identified.

Referring now to FIG. 6, a graph **600** has a horizontal axis with a scale in units of time in arbitrary units and a vertical axis with a scale in unit of current in arbitrary units. A graph **620** has a horizontal axis with a scale in units of time in arbitrary units and a vertical axis with a scale in unit of voltage in arbitrary units. A graph **640** has a horizontal axis with a scale in units of time in arbitrary units and a vertical axis with a scale in unit of voltage in arbitrary units.

A signal **602** is representative of a current signal in a motor winding A when a sinusoidal drive signal is used. The current signal **602** can be the same as or similar to the current signal **262** of FIG. 2. As described above, when a PWM drive signal is used, the current signal **602** can appear more complex, but the signal **602** is generally representative of an average current through the winding A. The current signal has zero crossings at time **606**, **608**.

A modulation signal **622** can be the same as or similar to the modulation signal **242** of FIG. 2. The modulation signal **622** can have six time periods or phases, of which four are shown **604a**, **604b**, **604c**, **604d**.

A PWM signal **642** can be generated, for example, by the PWM generator **108** of FIG. 1 in accordance with the modulation waveform **622** and can have times of high duty cycle **642a**, **642b** at times of peaks **622a**, **622b** of the modulation waveform **622** and times of lower duty cycle at times of other portions of the modulation waveform **622** in accordance with values of the modulation waveform **622**. The PWM signal **642** can be the signal actually applied to the motor winding A **104a** of the motor **104** of FIG. 1 for a sinusoidal drive.

Referring now to FIG. 7, PWM pulses **702**, **702'** are indicative of the PWM pulses **642** of FIG. 6 during negative polarity portions of the current signal **602**. A PWM pulse **704** is indicative of the PWM pulses **642** of FIG. 6 during positive polarity portions of the current signal **602**.

The PWM pulses **702**, **702'** have raised or transient portions **702b**, **702c**, **702b'**, **702c'** and steady state portions **702a**, **702a'**. In accordance with the discussion above in conjunction with FIGS. 5 and 5A, it will be appreciated that, when both transistors, e.g., FETs, of a half bridge are turned off, a voltage VoutA appearing on the associated motor winding temporarily goes above the motor voltage VM, or below ground, depending upon a polarity of the current in the motor winding, i.e., a polarity of the current signal **602**. It will also be appreciated that each major edge transition of the PWM signals **702**, **704**, **702'** is preceded by a short time period during which both of the FETs are turned off, otherwise, both FETs might simultaneously turn on, resulting in a short circuit between the motor voltage VM and ground. Thus, when the two FETs are turned off, the transient signal portions **702b**, **702c**, **704b**, **704c**, **702b'**, **702c'** result. The transient signal

13

portions **702b**, **702c**, **704b**, **704c**, **702b'**, **702c'** can occur for a short time period, for example, for about five hundred nanoseconds.

It will be apparent that the direction of the transient voltage signal portions **702b**, **702c**, **704b**, **704c**, **702b'**, **702c'** change direction upon each occurrence of a zero crossing of the current signal **602**, i.e., at times **606**, **608**. Thus, detection of changes in direction of the transient signal portions **702b**, **702c**, **704b**, **704c**, **702b'**, **702c'** can be used to identify a zero current in the associated motor winding.

Referring now to FIG. 7A, a graph **720** has a horizontal axis with a scale in units of time in arbitrary units and a vertical axis with a scale in unit of voltage in arbitrary units. A graph **740** has a horizontal axis with a scale in units of time in arbitrary units and a vertical axis with a scale in units of current in arbitrary units.

A signal **722** is representative of the PWM signal **642** of FIG. 6, but showing transient signal portions like the transient portions **702b**, **702c**, **704c**, **704d**, **702b'**, **702c'** of FIG. 7. A signal **742** is the same as or similar to the current signal **602** of FIG. 6.

Times t1-t9 occur during the transient signal portions. From discussion above in conjunction with FIGS. 5 and 5A, it will be apparent that the transient signal portions occur when both FETs of an associated half bridge circuit driving a motor winding are turned off.

For reasons described above in conjunction with FIGS. 5, 5A, and 7, at the time t6, the transient signal portion changes orientation coincident or nearly coincident with a zero crossing of the current signal **742**. Thus, the change of orientation of the transient signal portions can be used to detect a zero current crossing in a motor winding. In particular, at the times t1-t5, the transient signal portions extend above the motor voltage VM. Conversely, at the times t6-t9, the transient signal portions extend below ground. Another change or orientation (not shown) of the transient signal portions occurs at a next zero crossing of the current signal **742**, and can also be used to detect the next zero crossing.

In some embodiments, a circuit (see, e.g., comparators **808**, **810** shown below in FIG. 8) can be operable to sample the signal VoutA **722** to detect the signal transient portions only at or near to the times t1-t9, and also at other similar times that follow. The times t1-t9 and similar times that follow are known, since both FETs are momentarily turned off at those times. In other embodiments, the signal **722** can be continually sampled to detect the transient signal portions.

In some embodiments, the changes of orientations of the transient signal portions can be detected with two comparators. Both zero crossings of the current signal **742** can be detected. However, in other embodiments, one comparator can be used to detect the presence or absence of transient signal portions that either extend upward or that extend downward. Still, both zero crossings of the current signal **742** can be detected with one comparator.

Referring now to FIG. 8, a zero current detection module **802** can be the same as or similar to the current measurement module **144** of FIG. 1.

The zero current detection module **802** can include a first comparator **808** coupled to the three motor windings via a selectable switch **804**. The zero current detection module **802** can also include a second comparator **810** coupled to the three motor windings via a selectable switch **806**. The first comparator **808** can be coupled to receive a reference voltage equal to or close to the motor voltage VM. The second comparator **810** can be coupled to receive a reference voltage equal to or close to ground.

14

The first comparator **808** is configured to generate an output signal **808a** indicative of voltage on a selected motor winding going above the motor voltage. The second comparator **810** is configured to generate an output signal **810a** indicative of voltage on a selected motor winding going below ground. Thus, in operation, the first comparator **808** operable to detect the positive transient signal portions **702b**, **702c**, **702b'**, **702c'** of the PWM signal of FIG. 7 associated with a sinusoidal motor drive. Similarly, in operation, the second comparator **810** is operable to detect the negative transient signal portions **704b**, **704c** of the PWM signal of FIG. 7 associated with a sinusoidal motor drive. As described above, edges of these signal portions can be used to identify a zero current crossing in an associated motor winding.

The zero current detection module **802** can also include a multiplexer **812** coupled to receive the output signal **808a**, **810a** and configured to generate and output single **812a** representative of a selected one of the output signals **808a**, **810a**.

The multiplexer **812** can be coupled to receive a control signal **814** from the modulation signal generation module **146**, i.e., a control signal **146d** of FIG. 1. The switches **804**, **806** can be coupled to receive other control signals (not shown) from the modulation signal generation module **146**.

The modulation signal generation module **146** can use a variety of types of logic to identify a zero current crossing in one or more of the motor windings. For example, in accordance with the discussion above in conjunction with FIGS. 7 and 7A, for a PWM sinusoidal motor drive signal, the output signals **808a**, **810a** can be used to identify a change in direction of the transient signal portions **702b**, **702c**, **704b**, **704c**, **702b'**, **702c'** of the PWM signal **642**. Essentially, the multiplexer **812** can switch to view the other comparator whenever detection is made of a particular direction of the transient signal portions.

In some embodiments, the switches are not used and only one motor winding is used to provide signals to the comparators **808**, **810**. In some embodiments, only one comparator is used and the multiplexer **812** is not necessary. A variety of different types of logic can be used by the modulation signal generation module **146** to identify a zero crossing of a current through a motor winding by using the above described technique of detecting when a voltage on a motor winding goes above the motor voltage VM and/or below ground.

Referring now to FIG. 9, a graph **900** has a horizontal axis in units of time in arbitrary units and a vertical axis with both units of pulse width modulation (PWM) duty cycle in arbitrary units and in units of current in arbitrary units. The graph **900** is representative of the above-described start-up mode of operation followed by the above-described exemplary normal mode of operation.

On the time axis, a first ramp-up time period **906a** and a second ramp-up time period **906b** are indicative of the above-described start-up mode of operation. Taken together, the first ramp-up time period and the second ramp-up time period are referred to herein as either a ramp-up time period or a start-up time period.

A coasting time period **906b** is indicative of a transition time between the start of mode of operation and the above-described exemplary normal mode of operation. A normal mode time period **906d** is indicative of the normal mode of operation.

A curve **904** is indicative of a peak pulse width modulation duty cycle, i.e., is indicative of values of the start-up mode demand signal **148a** of FIG. 1, for example at peaks of the modulation waveforms **242**, **244**, **246** of FIG. 2. As described above, pulse width duty cycle is related to amplitudes of the drive signal **124**, **126**, **128** (FIG. 1) applied to the motor **104**.

15

During the first ramp-up time period **904a**, the peak PWM duty cycle (the start-up mode demand signal **148b**) increases rapidly from a low duty cycle, for example, zero percent peak duty cycle or two percent peak duty cycle. During the second ramp-up time period **906b**, the peak PWM duty cycle (the

start-up mode demand signal **148b**) increases less rapidly. While not shown, during the first ramp-up time period **906a**, as will become apparent from discussion below in conjunction with FIG. 12, the start-up mode theta signal **148c** of FIG. 1 can also increase, resulting in an increase in a frequency of the modulation waveforms, i.e., modulation envelope **a**, **146a**, **146b**, **146c** of FIG. 1, exemplary versions of which are shown as waveforms **242**, **244**, **246** of FIG. 2. An increase in frequency of the modulation waveforms is equivalent to an increase in rate of the modulation waveforms. Also, while not shown, during the second ramp-up time period **906b**, the start-up mode theta signal **148c** of FIG. 1 can increase, again resulting in an increase in the frequency of the modulation waveforms.

In some embodiments, the first ramp-up time period **906a** is dominated by an increase in the peak PWM duty cycle. In some embodiments, the second ramp-up time period **906b** is dominated by an increase in frequency of the modulation waveforms.

Increases in the peak PWM duty cycle during the first ramp-up time period **906a** and during the second ramp-up time period **906b** are shown to increase linearly and continuously. In other embodiments, one of or both of the increases can be nonlinear and continuous. In other embodiments, one of or both of the increases can be discontinuous.

In some other embodiments, there is only one ramp-up time period during the start-up mode of operation, and during the one ramp-up time period, the peak PWM duty cycle can increase linearly and continuously in some embodiments, nonlinearly and continuously in other embodiments, and discontinuously in still other embodiments. Similarly, during the one ramp-up time period, the frequency of the modulation waveforms can increase linearly and continuously in some embodiments, nonlinearly and continuously in other embodiments, and discontinuously in still other embodiments.

During the coasting time period **906c**, the peak PWM duty cycle is brought to zero, which is indicative of the drive signals **124**, **126**, **128** of FIG. 1 being turned off. As described above, the back EMF signal on a motor winding, generated when the motor is rotating, can be observed when there are no drive signals applied to the motor. Thus, the coasting time period **904c** can have a time duration beginning at the time of stopping the drive signals and ending when a particular back EMF signal is detected. This is further described below in conjunction with FIG. 10.

After the coasting time period, an intermediate peak PWM duty cycle **904d** is applied to the motor and the motor operates in the normal mode of operation thereafter.

A signal **902** is representative of current flowing through one of the motor windings, for example motor winding A **104a** of FIG. 1. During the first ramp-up time period, a portion **902a** of the current signal **902** increases primarily in amplitude, and less so in frequency. During the second ramp-up time period, a portion **902b** of the current signal **902** increases primarily in frequency, and less so in amplitude. During the coasting time period, a portion **902c** of the current signal **902** is representative of a zero current in the motor winding. During the normal mode time period, a portion **902d** of the current signal **902** is representative of the normal mode of operation.

It can be seen that, at the end of the second ramp-up time period, the drive signal to the motor winding that results in the

16

current signal **902** is stopped and the current signal **902** goes to zero current. Similarly, at the beginning of the normal mode time period, the current signal **902** begins at a phase such that the current starts at zero.

The coasting time period is described more fully below in conjunction with FIG. 10.

Referring now to FIG. 10, signals **1000** are shown with a horizontal time scale in arbitrary units. A vertical scale is in units of current in arbitrary units.

A second ramp-up time period can be the same as or similar to the second ramp-up time period of FIG. 9. A coasting time period shown in FIG. 10 can be the same as or similar to the coasting time period shown above in conjunction with FIG. 9. A normal mode time period shown in FIG. 10 can be the same as or similar to the normal mode time period shown above in conjunction with FIG. 9.

Here, the currents in all three of the motor windings of the motor **104** of FIG. 1 are shown at the end of the second ramp-up time period. As described above in conjunction with FIG. 9, at the end of the second ramp-up time period, i.e., at the beginning of the coasting time period, as soon as the current **iA** in the winding A **104a** is zero, all three motor drive signals are stopped, in which case, during the coasting time period, the current in winding A stays at zero and the currents in the other two windings rapidly approach zero.

In operation, at some time during the coasting time period, the back EMF signal **1002** on the winding A passes through zero volts. Zero crossing of the back EMF is indicative of a reference rotational position of the rotation of the motor. When the zero voltage is detected on the winding A, all three motor drive signals are again started resulting in the current waveforms shown during the normal mode of operation. In particular, it should be noted that, with this arrangement, the current on winding A (and the currents at all the other windings) start-up in the normal mode of operation at the same phases that they were in at the end of the ramp-up time period. In this way, the motor achieves the normal mode of operation without a phase discontinuity in the signals that drive the motor.

Referring now to FIG. 11, a start-up control module **1100** can be the same as or similar to the start-up control module **148** of FIG. 1. The start-up control module **1100** essentially controls operation of the motor control circuit **102** of FIG. 1 during the first and second ramp-up time periods and the coasting time period of FIGS. 9 and 10.

The start-up control module **1100** can be coupled to receive a zero current signal **1120**. The zero current signal **1120** can be the same as or similar to the detected zero current signal **144a** of FIG. 1.

The start-up control module **1100** can also be coupled to receive one or more back EMF signals **1122**. The back EMF signals can be this same as or similar to the back EMF signals **150** of FIG. 1.

The start-up control module **1100** can also be coupled to receive a system clock signal **1124**.

The start-up control module **1100** can also be coupled to receive a selection signal **1118a** from a resistor divider **1118**. The resistor divider **1118** can be the same as or similar to the resistor divider **152** of FIG. 1.

The start-up control module **1100** can also be coupled to receive a motor voltage signal **1116a** from a resistor divider **1116**. The resistor divider **1116** can be the same as or similar to the resistor divider **154** of FIG. 1.

The start-up control module **1100** is configured to generate a start-up mode theta signal **1104c**. The start-up mode theta signal **1104c** can be the same as or similar to the start-up mode theta signal **148c** of FIG. 1.

17

The start-up control module **1100** is also configured to generate a start-up mode demand signal **1104a**. The start-up mode demand signal **1104a** can be the same as or similar to the start-up mode demand signal **148a** of FIG. 1.

The start-up control module **1100** is also configured to generate a mode control signal **1104b**. The mode control signal **1104b** can be the same as or similar to the control signal **148b** of FIG. 1.

The start-up control module **1100** can include a switch **1110** is configured to toggle back and forth between the motor voltage signal **1116a** and the selection signal **1118a**. An analog-to-digital converter **1112** is coupled to receive an output signal from the switch **1110**. The analog-to-digital converter **1112** is configured to generate a digital output signal **1112a** representative of at least one of the motor voltage signal **1116a** or the selection signal **1118a**.

The start-up control module **1100** can include decoding logic **1114** coupled to receive the digital signal **1112a**. In response to the digital signal **1112a**, the decoding logic **1114** can generate a control signal **1114a** representative of a selected one of a plurality of states. It will become apparent from discussion below, that the selected one of the plurality of states is representative of a selected one of a plurality of sets of parameter values that determine characteristics of drive signals applied to the motor **104** of FIG. 1 during the start-up mode of operation. Thus, one of the plurality of sets of parameter values is selected in accordance with at least one of the selection signal **1118a** or the motor voltage signal **1116a**, and therefore, by a user.

The plurality of sets of parameter values **1106** can be retained within or proximate to the start-up control module **1100**. The parameter values **1106** can be retained in a variety of ways. In some embodiments, the sets of parameter values **1106** are retained in a storage device, for example, a ROM, a PROM, or an EEPROM. However, in order to minimize use of silicon surface area in fabrication of the motor control circuit **102** of FIG. 1, in some embodiments, the parameter values **1106** can merely be hard wired bits, wherein all of the bits are available at the same time.

All of the parameter values can be received by a multiplexer **1108**. In response to the control signal **1114a**, the multiplexer **1108** can present a selected one of the plurality of sets of parameter values as a signal **1108a**, which can be either a serial digital signal or a parallel digital signal.

A start-up theta and demand module **1104** can include a theta ramp generator similar to the theta ramp generator **404** of FIG. 4. In response to the selected one of the plurality of sets of parameter values within the signal **1108a**, the start-up theta and demand module **1104** can generate the signals **1104a**, **1104b**, **1104c**.

The start-up control module **1100** can include a pulse width filter **1102** coupled to receive the zero current signal **1120**. The pulse width filter **1102** can be operable to remove very short pulses (e.g., transient noise pulses) to provide a more clean zero current signal **1102a**. The back EMF signal **1122** is used by the start-up theta and demand module **1104** for the synchronization process at the end of the coasting time period described above in conjunction with FIG. 10.

The zero current signal **1120** is used by the start-up theta and demand module **1104** to identify the zero current at the end of the ramp-up time period, i.e., the end of the start-up mode of operation, represented in FIG. 10.

Referring now to FIG. 12, a table shows ten exemplary parameters that can be used during the start-up mode of operation, and in particular, during a start-up mode of operation that includes both the first and second ramp-up time periods described above in conjunction with FIG. 9. While

18

particular parameters are shown it should be recognized that other parameters can be used without departing from the intent, including more than ten parameters or fewer than ten parameters. Definitions of the various exemplary parameters are listed below.

fixedIniDutyIn—controls the initial peak PWM duty cycle during first amp up time period

alignDutyIncrTime—controls the peak PWM duty cycle increment time during the first ramp-up time period

alignDutyIncr—controls the peak PWM duty cycle increment during the first ramp-up time period

alignThetaIncrTime—control the start-up mode theta increment time during the first ramp-up time period

iniRampDuty—controls the initial peak PWM duty cycle during the second ramp-up time period

dutyIncr—controls the peak PWM duty cycle increment amount during the second ramp-up time period

freqUpdateTime—controls the ramp-up frequency (of modulation waveforms) changing time during the second ramp-up time period

iniFreqSel—controls the initial ramp-up frequency (of the modulation waveforms) during the second ramp-up time period

noOffFreq—controls the total number of frequencies (of modulation waveforms) within the second ramp-up time period

iniDutyAfterCoast—control the peak PWM duty cycle at end of the coasting time period

Exemplary numbers of bits are shown for each parameter, however, in other embodiments, other numbers of bits can be used.

Twenty four exemplary sets of parameter values are shown.

Only a first set of specific exemplary parameter values is shown due to the characteristic that the specific parameter values in each set of values can vary greatly depending upon the types of motors to which the motor control circuit is applied.

As described above, one of the sets of parameter values (here, one set from among exemplary Set 1 to exemplary Set 24) is selected in accordance with the motor voltage signal **1116a** and/or the selection signal **1118a** of FIG. 11. Thus, the selection can be made by a user by selection of the resistor divider **1118** of FIG. 11 in accordance with a type of motor being driven by the motor control circuit **102** of FIG. 1 and in accordance with a load presented to the motor.

Some parameter values can be fixed and the same in each one of the columns of FIG. 12, however, in other embodiments, none of the values are fixed. While particular values are shown in the Set 1 column of FIG. 12, other values could also be used. Useful ranges of parameter values for the various columns of FIG. 12 are listed below:

fixedIniDutyIn—0% to 10%

alignDutyIncrTime—1 ms to 50 ms

alignDutyIncr—0.1% to 5%

alignThetaIncrTime—1 ms to 50 ms

iniRampDuty—5% to 50%

dutyIncr—0.1% to 10%

freqUpdateTime—10 ms to 500 ms

iniFreqSel—0.5 HZ to 20 Hz

noOffFreq—1 to 100

iniDutyAfterCoast—5% to 50%

Referring now to FIG. 13, a chart shows exemplary logic by which the start-up control module of FIG. 11 can use that the motor voltage signal **1116a** and the selection signal **1118a** of FIG. 11 can be combined in order to select one of the twenty four sets of parameter values listed in FIG. 12. The listed selection values 0-15 correspond to arbitrary voltage

19

values of the selection signal **152a** of FIG. 1. Each selection value can be determined in accordance with an arbitrary range of voltages, for example within plus or minus twenty percent of a respective voltage value.

While the chart of FIG. 13 is representative of a particular logic used by the decoding logic module **1114** of FIG. 11, it should be recognized that any number of other logics could be used to combine the motor voltage signal and the selection signal.

In some embodiments, the motor voltage signal **1116a** is not used at all, in which case, there is a one-to-one mapping between each selection value and a set of parameter values. Thus, there can be only sixteen sets of parameter values.

While twenty-four sets of parameter values are shown and described above in conjunction with FIG. 12, and while sixteen-sets of parameter values are described above, in alternate embodiments, there can be any number of sets of parameter values, so long as there are at least two sets of parameter values.

It should be appreciated that FIG. 14 shows a flowchart corresponding to the below contemplated technique which would be implemented in a motor control circuit **102** (FIG. 1). Rectangular elements (typified by element **1402** in FIG. 14), herein denoted "processing blocks," represent computer software instructions or groups of instructions. Diamond shaped elements (typified by element **1418** in FIG. 14), herein denoted "decision blocks," represent computer software instructions, or groups of instructions, which affect the execution of the computer software instructions represented by the processing blocks.

Alternatively, the processing and decision blocks represent steps performed by functionally equivalent circuits such as a digital signal processor circuit or an application specific integrated circuit (ASIC). The flow diagrams do not depict the syntax of any particular programming language. Rather, the flow diagrams illustrate the functional information one of ordinary skill in the art requires to fabricate circuits or to generate computer software to perform the processing required of the particular apparatus. It should be noted that many routine program elements, such as initialization of loops and variables and the use of temporary variables are not shown. It will be appreciated by those of ordinary skill in the art that unless otherwise indicated herein, the particular sequence of blocks described is illustrative only and can be varied without departing from the spirit of the invention. Thus, unless otherwise stated the blocks described below are unordered meaning that, when possible, the steps can be performed in any convenient or desirable order.

Referring now to FIGS. 14 and 14A taken together, a method **1400** is indicative of an exemplary way that the various parameters listed above can be used during the start-up mode of operation in the motor control circuit **102** of FIG. 1, and, in particular, during a start-up mode of operation that has the first ramp-up time period and the second ramp-up time period shown and described above in conjunction with FIG. 9. However, it will be understood that other methods can be used to provide the start-up mode of operation using at least the selection signal **152a** of FIG. 1, including, as described above, a start-up mode of operation that has only one ramp-up time period.

Reference is made throughout the discussion of FIGS. 14 and 14A to hardware elements of FIG. 1. It is assumed that the method **1400** begins at a time when an electric motor, to which the motor control circuit **102** is coupled, is not rotating.

It will be recognized from discussion below that blocks **1402-1418** correspond to functions of the start-up control module **148** during the first ramp-up time period described

20

above in conjunction with FIG. 9. Blocks **1424-1438** correspond to functions of the start-up control module **148** during the second ramp-up time period described above in conjunction with FIG. 9. Blocks **1440-1444** correspond to functions of the start-up control module **148** during the coasting time period described above in conjunction with FIG. 9. Blocks **1446-1448** correspond to functions of the start-up control module **148** and the overall motor control circuit **102** during the normal mode of operation described above in conjunction with FIG. 9 and various other ones of the figures.

The exemplary method **1400** begins at step **1402**, where the start-up control module **148** of FIG. 1 sets the mode control signal **148b** to a state indicative of a start-up mode of operation.

At block **1404**, the start-up control module **148** detects a value of the selection signal **152a**, e.g., an analog voltage value of the selection signal **152a**.

At block **1406**, the start-up control module **148** detects a value of the motor voltage signal **154a**, e.g., an analog voltage value of the motor voltage signal **154a**.

At block **1408**, the start-up control module **148** identifies a start-up parameter set, i.e., one of the columns of FIG. 12, in accordance with the discussion above in conjunction with FIGS. 11, 12, and 13. In some embodiments, the start-up control module **148** uses both the selection signal **152a** and the motor voltage signal **154a** to identify a set of parameter values from a plurality of sets of parameter values as described above in conjunction with FIGS. 12 and 13. However, in some other embodiments, as described above, the start-up motor control module **148** does not use the motor voltage signal **154a**, and the determination of which set of parameter values to use is made only in accordance with the selection signal **152a**.

At block **1410**, the start-up control module **148** sets the first ramp-up time period theta signal, (i.e., start-up mode theta signal **148c** during the first ramp-up time period) to an initial value, for example, to be equal to a parameter value of align-ThetaIncrTime*256.

At block **1412**, the start-up control module **148** sets the first ramp-up time period speed demand signal (i.e., start-up mode demand signal **148a** during the first ramp-up time period, i.e. the peak duty cycle of PWM waveforms) in accordance with the parameter fixedIniDutyIn of the selected parameter value set of FIGS. 12 and 13.

Values set at blocks **1410** and **1412** cause motor drive signals **124**, **126**, **128** to begin driving the motor **104**.

At block **1414**, the motor control circuit **102** waits (while generating the motor drive signals **124**, **126**, **128**) in accordance with the parameter alignDutyIncrTime of the selected parameter value set.

At block **1416**, the start-up control module **148** increments the first ramp-up time period demand signal in accordance with the parameter alignDutyIncr of the selected parameter value set.

In parallel with blocks **1414** and **1416**, at block **1420**, the motor control circuit **102** waits (while generating the motor drive signals **124**, **126**, **128**) in accordance with the parameter alignThetaIncrTime of the selected parameter value set. At block **1422**, the start-up control module **148** increments the first ramp-up time period theta signal (i.e., start-up mode theta signal **148c** during the first ramp-up time period), for example, by one count value (e.g., for embodiments in which the theta signal counts from zero to two hundred fifty-five). In other embodiments, a value greater than one count value can be used.

At block **1418** the start-up control module **148** detects whether an end of the first ramp-up time period has occurred.

21

In some embodiments, the end of the first ramp-up time period (see, e.g., FIG. 9) can be detected in accordance with an end of one cycle of the start-up mode theta signal **148c** of FIG. 1. It will be understood from discussion above that the start-up mode theta signal **148c** is comprised of values that ramp-up in value. The end of a theta cycle can constitute a last value of the ramp-up of the theta signal **148c**.

In other embodiments, an end of the first ramp-up time period can be detected in accordance with any number of cycles of the start-up mode theta signal **148c**, where the start-up mode theta signal **148c** ramps up then resets to an initial value and ramps up again in each cycle.

If an end of the first ramp-up time period is detected, then the process proceeds to block **1424**. At block **1424**, the second ramp-up time period begins (see, e.g., FIG. 9)

At block **1424**, the start-up control module **148** sets the first ramp-up time period speed demand signal (i.e., start-up mode demand signal **148a** during the second ramp-up time period, i.e. the peak duty cycle of PWM waveforms) in accordance with the parameter *iniRampDuty* of the selected parameter value set of FIGS. 12 and 13.

At block **1426**, the start-up control module **148** sets the second ramp-up time period theta signal, (i.e., start-up mode theta signal **148c** at the start of the second ramp-up time period) in accordance with the parameter *iniFreqSel* of the selected parameter value set of FIGS. 12 and 13.

At block **1428**, (FIG. 14A) the start-up control module **148** continuously ramps the second ramp-up time period theta signal (i.e., the start-up mode theta signal **148c**) in order to generate periodic and repetitive cycles of a ramping signal. This results in the drive signals **124**, **126**, **128** having a plurality of cycles.

At block **1430**, the motor control circuit **102**, and the start-up control module **148** in particular, continues to generate cycles of the start-up mode theta signal **148c** (while generating a corresponding cycles of the motor drive signals **124**, **126**, **128**) until a time in accordance with the parameter *freqUpdateTime* of the selected parameter value set of FIGS. 12 and 13.

At block **1432**, the start-up control module **148** increments the second ramp-up time period demand signal (i.e., the start-up mode demand signal **148a**) in accordance with the parameter *dutyIncr* of the selected parameter value set of FIGS. 12 and 13.

In parallel block with **1432**, at block **1434**, the start-up control module **148** sets the second ramp-up time period theta signal (i.e., the start-up mode theta signal **148c**) to a new rate (i.e., frequency) in accordance with a frequency increment, for example, a three Hz increment. However, the increment can be any value in a range from about one Hz to about 100 Hz. In some embodiments, this value is selected as another value (not shown) within a set of selected parameter values from FIG. 12.

At block **1444**, the start-up control module **148** identifies if the number of frequency updates at block **1446** is above a value in accordance with the parameter *NoOffFreq* of the selected parameter value set of FIGS. 12 and 13.

If the number of frequency updates has been exceeded, then the process proceeds to block **1438**. If the number of frequency updates has not been exceeded, then the process returns to block **1430**.

At block **1438** the start-up control module **148** waits for the current in a selected one or more of the windings of the motor **104** to achieve a current approximately equal to zero. The time at which the current reaches zero corresponds to the beginning of the coasting time shown in FIG. 9.

22

At block **1440**, during the coasting time period of FIG. 6, the start-up control module **148** shuts down the start-up mode command signal **148a** and the start-up mode theta signal **148c** in order to shut down the drive signals **124**, **126**, **128** to the motor **104** to enter the coasting time period of FIG. 9.

At block **1442**, the start-up control module **148** uses the back EMF signal **150**, in accordance with the discussion above in conjunction with FIG. 10, in order to identify an end of the coasting time period. At block **1442**, if the end of the coasting time period is not yet detected, then the process returns to block **1440** in a loop. At block **1442**, if the end of the coasting time period is detected, then the process proceeds to block **1444**.

At block **1444**, the start-up control module **148** sets the coasting time period speed demand signal (i.e., the start-up mode demand signal **148a**) in accordance with the parameter *iniDutyAfterCoast* of the selected parameter value set of FIGS. 12 and 13.

At block **1446**, the start-up control module **148** sets the mode control signal **148b** to a state indicative of the normal mode of operation, at which time the start-up control module **148** relinquishes control of the motor control circuit **102** to the modulation signal generation module **146**.

At block **1448**, the motor control circuit **102** runs in the normal mode of operation using the normal mode demand signal **107a** and the normal mode theta signal **406a** of FIG. 4.

The above process describes a two-step approach for starting up an electric motor, namely, a two-step approach using the first ramp-up time period and the second ramp-up time period described above in conjunction with FIG. 9. In general, starting up the motor can use only one ramp-up time period, or more than two ramp-up time periods.

While particular parameters and parameter values are described above in conjunction with FIG. 12, and particular logic is described above in conjunction with FIG. 13, other parameters, other parameter values, and other logic can be used.

All references cited herein are hereby incorporated herein by reference in their entirety.

Having described preferred embodiments, which serve to illustrate various concepts, structures and techniques, which are the subject of this patent, it will now become apparent to those of ordinary skill in the art that other embodiments incorporating these concepts, structures and techniques may be used. Accordingly, it is submitted that that scope of the patent should not be limited to the described embodiments but rather should be limited only by the spirit and scope of the following claims.

What is claimed is:

1. A method of driving, with a motor control circuit, a multi-phase motor having a plurality of motor windings, the method comprising:

receiving, from outside of the motor control circuit, a selection signal;

identifying, with the motor control circuit, a set of parameter values from among a plurality of different sets of parameter values retained on the motor control circuit, wherein the plurality of different sets of parameter values is indicative of a corresponding plurality of different start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings, wherein at least two of the plurality of different sets of parameter values are indicative of rotation of the multi-phase motor in the same direction, the identifying done in accordance with the selection signal;

determining, in accordance with the identified set of parameter values, with the motor control circuit, the

23

start-up signal characteristics of the plurality of drive signals coupled to the plurality of motor windings, wherein the determined start-up signal characteristics of the plurality of drive signals comprise a respective ramped start-up of the electric motor during a respective ramp-up time period during a start-up mode of operation; and

generating, with the motor control circuit, the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning.

2. The method of claim 1, further comprising:

receiving, from outside of the motor control circuit, a motor voltage signal, wherein the identifying the set of parameter values is done in accordance with both the selection signal and the motor voltage signal.

3. The method of claim 2, wherein the generating the plurality of drive signals comprises:

generating a corresponding plurality of modulated PWM waveforms, the plurality of modulated PWM waveforms having respective duty cycles that change with time according to a sine-drive modulation envelope, wherein the sine-drive modulation envelope comprises a frequency, wherein each one of the plurality of modulated PWM waveforms has a peak duty cycle, wherein the peak duty cycle of each one of the plurality of modulated PWM waveforms is related to an amplitude of a respective one of a plurality of sinusoidal current signals carried by the plurality of motor windings, and wherein the frequency of the modulation envelope is related to a frequency of the plurality of sinusoidal current signals.

4. The method of claim 3, wherein the ramped start-up comprises a ramp-up of at least one of the peak duty cycle of the modulated PWM waveform or the frequency of the sine-drive modulation envelope, wherein time varying characteristics of at least one of the peak duty cycle or the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

5. The method of claim 1, wherein the generating the plurality of drive signals comprises:

generating a corresponding plurality of modulated PWM waveforms, the plurality of modulated PWM waveforms having respective duty cycles that change with time according to a sine-drive modulation envelope, wherein the sine-drive modulation envelope comprises a frequency, wherein each one of the plurality of modulated PWM waveforms has a peak duty cycle, wherein the peak duty cycle of each one of the plurality of modulated PWM waveforms is related to an amplitude of a respective one of a plurality of sinusoidal current signals carried by the plurality of motor windings, and wherein the frequency of the modulation envelope is related to a frequency of the plurality of sinusoidal current signals.

6. The method of claim 5, wherein the ramped start-up comprises a ramp-up of the peak duty cycle of the modulated PWM waveform during a ramp-up time period, wherein time varying characteristics of the peak duty cycle during the ramp-up time period are selected in accordance with the identified set of parameter values.

7. The method of claim 5, wherein the ramped start-up comprises a ramp-up of the frequency of the sine-drive modulation envelope during the ramp-up time period, wherein time varying characteristics of the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

24

8. The method of claim 5, wherein the ramped start-up comprises:

a ramp-up of the peak duty cycle of the modulated PWM waveform during the ramp-up time period, wherein time varying characteristics of the peak duty cycle during the ramp-up time period are selected in accordance with the identified set of parameter values; and

a ramp-up of the frequency of the sine-drive modulation envelope during the ramp-up time period, wherein time varying characteristics of the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

9. The method of claim 8, wherein the ramp-up time period is also selected in accordance with the identified set of parameter values.

10. The method of claim 5, wherein the ramp-up time period comprises a first ramp-up time period followed by a second different ramp-up time period.

11. The method of claim 10, wherein the ramped start-up comprises:

a ramp-up of at least the peak duty cycle of the modulated PWM waveform during the first ramp-up time period, wherein time varying characteristics of the peak duty cycle during the first ramp-up time period are selected in accordance with the identified set of parameter values, and

a ramp-up of at least the frequency of the sine-drive modulation envelope during the second ramp-up time period, wherein time varying characteristics of the frequency during the second ramp-up time period are selected in accordance with the identified set of parameter values.

12. The method of claim 11, wherein the first and second ramp-up time periods are also selected in accordance with the identified set of parameter values.

13. The method of claim 10, wherein the determined start-up signal characteristics comprise:

first ramp-up characteristics during the first ramp-up time period; and

second different ramp-up characteristics during the second ramp-up time period.

14. The method of claim 13, wherein the first ramp-up characteristics comprise first characteristics of the plurality of drive signals beginning at a time when the multi-phase motor is not spinning and ending at an end of the first ramp-up time period, wherein the first ramp-up time period comprises a first at least one cycle of the plurality of sinusoidal current signals, and wherein the second ramp-up characteristics comprise second characteristics of the plurality of drive signals beginning at a beginning of the second ramp-up time period and ending at an end of the second ramp-up time period, wherein the second ramp-up time period comprises a second at least one cycle of the plurality of sinusoidal current signals, wherein an end of the first at least one cycle is continuous in phase with a start of the second at least one cycle.

15. The method of claim 5, wherein the generating the plurality of drive signals comprises:

generating the plurality of drive signals such that, at an end of the ramp-up time period, a last one of the plurality of cycles of a selected one of the plurality of sinusoidal current signals ends at a zero current.

16. The method of claim 15, further comprising

stopping the plurality of drive signals for a coasting time period following the end of the ramp-up time period;

detecting a back EMF signal indicative of a zero back EMF voltage on a selected one of the plurality of motor wind-

25

ings while the plurality of drive signals are stopped, the detected back EMF signal indicative of an end of the coasting time period; and

driving the plurality of motor windings with the plurality of sinusoidal current signals in a normal mode of operation in response to the detecting, wherein, in the normal mode of operation, a first cycle of a sinusoidal current signal on the selected one of the plurality of motor windings begins at zero current and at a phase continuous with a phase of the last one of the plurality of cycles of the sinusoidal current signal on the selected one of the plurality of motor windings at the end of the ramp-up time period.

17. The method of claim 1, wherein a value of the selection signal is determined based upon a load upon the multi-phase motor.

18. A motor control circuit for driving a multi-phase motor having a plurality of motor windings, the motor control circuit comprising a start-up control module configured to:

receive, from outside of the motor control circuit, a selection signal;

identify set of parameter values from among a plurality of different sets of parameter values retained on the motor control circuit, wherein the plurality of different sets of parameter values is indicative of a corresponding plurality of different start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings, wherein at least two of the plurality of different sets of parameter values are indicative of rotation of the multi-phase motor in the same direction, the identifying done in accordance with the selection signal; and determine, in accordance with the identified set of parameter values, the start-up signal characteristics of the plurality of drive signals coupled to the plurality of motor windings, wherein the determined start-up signal characteristics of the plurality of drive signals comprise a respective ramped start-up of the electric motor during a respective ramp-up time period during a start-up mode of operation; wherein the motor control circuit is configured to:

generate the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning.

19. The motor control circuit of claim 18, wherein the start-up control module is further configured to:

receive a motor voltage signal, and to identify the set of parameter values in accordance with both the selection signal and the motor voltage signal.

20. The motor control circuit of claim 19, wherein the motor control circuit is configured to generate the plurality of drive signals by:

generating a corresponding plurality of modulated PWM waveforms, the plurality of modulated PWM waveforms having respective duty cycles that change with time according to a sine-drive modulation envelope, wherein the sine-drive modulation envelope comprises a frequency, wherein each one of the plurality of modulated PWM waveforms has a peak duty cycle, wherein the peak duty cycle of each one of the plurality of modulated PWM waveforms is related to an amplitude of a respective one of a plurality of sinusoidal current signals carried by the plurality of motor windings, and wherein the frequency of the modulation envelope is related to a frequency of the plurality of sinusoidal current signals.

21. The motor control circuit of claim 20, wherein the ramped start-up comprises a ramp-up of at least one of the peak duty cycle of the modulated PWM waveform or the

26

frequency of the sine-drive modulation envelope, wherein time varying characteristics of at least one of the peak duty cycle or the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

22. The motor control circuit of claim 18, wherein the motor control circuit is configured to generate the plurality of drive signals by:

generating a corresponding plurality of modulated PWM waveforms, the plurality of modulated PWM waveforms having respective duty cycles that change with time according to a sine-drive modulation envelope, wherein the sine-drive modulation envelope comprises a frequency, wherein each one of the plurality of modulated PWM waveforms has a peak duty cycle, wherein the peak duty cycle of each one of the plurality of modulated PWM waveforms is related to an amplitude of a respective one of a plurality of sinusoidal current signals carried by the plurality of motor windings, and wherein the frequency of the modulation envelope is related to a frequency of the plurality of sinusoidal current signals.

23. The motor control circuit of claim 22, wherein the ramped start-up comprises a ramp-up of the peak duty cycle of the modulated PWM waveform during a ramp-up time period, wherein time varying characteristics of the peak duty cycle during the ramp-up time period are selected in accordance with the identified set of parameter values.

24. The motor control circuit of claim 22, wherein the ramped start-up comprises a ramp-up of the frequency of the sine-drive modulation envelope during the ramp-up time period, wherein time varying characteristics of the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

25. The motor control circuit of claim 22, wherein the ramped start-up comprises:

a ramp-up of the peak duty cycle of the modulated PWM waveform during the ramp-up time period, wherein time varying characteristics of the peak duty cycle during the ramp-up time period are selected in accordance with the identified set of parameter values; and

a ramp-up of the frequency of the sine-drive modulation envelope during the ramp-up time period, wherein time varying characteristics of the frequency during the ramp-up time period are selected in accordance with the identified set of parameter values.

26. The motor control circuit of claim 25, wherein the ramp-up time period is also selected in accordance with the identified set of parameter values.

27. The motor control circuit of claim 22, wherein the ramp-up time period comprises a first ramp-up time period followed by a second different ramp-up time period.

28. The motor control circuit of claim 27, wherein the ramped start-up comprises:

a ramp-up of at least the peak duty cycle of the modulated PWM waveform during the first ramp-up time period, wherein time varying characteristics of the peak duty cycle during the first ramp-up time period are selected in accordance with the identified set of parameter values, and

a ramp-up of at least the frequency of the sine-drive modulation envelope during the second ramp-up time period, wherein time varying characteristics of the frequency during the second ramp-up time period are selected in accordance with the identified set of parameter values.

29. The motor control circuit of claim 28, wherein the first and second ramp-up time periods are also selected in accordance with the identified set of parameter values.

27

30. The motor control circuit of claim 27, wherein the determined start-up signal characteristics comprise:

- first ramp-up characteristics during the first ramp-up time period; and
- second different ramp-up characteristics during the second ramp-up time period.

31. The motor control circuit of claim 30, wherein the first ramp-up characteristics comprise first characteristics of the plurality of drive signals beginning at a time when the multi-phase motor is not spinning and ending at an end of the first ramp-up time period, wherein the first ramp-up time period comprises a first at least one cycle of the plurality of sinusoidal current signals, and wherein the second ramp-up characteristics comprise second characteristics of the plurality of drive signals beginning at a beginning of the second ramp-up time period and ending at an end of the second ramp-up time period, wherein the second ramp-up time period comprises a second at least one cycle of the plurality of sinusoidal current signals, wherein an end of the first at least one cycle is continuous in phase with a start of the second at least one cycle.

32. The motor control circuit of claim 22, wherein the generating the plurality of drive signals comprises:

- generating the plurality of drive signals such that, at an end of the ramp-up time period, a last one of the plurality of cycles of a selected one of the plurality of sinusoidal current signals ends at a zero current.

33. The motor control circuit of claim 32, wherein the start-up control module is further configured to:

- stop the plurality of drive signals for a coasting time period following the end of the ramp-up time period; and
- detect a back EMF signal indicative of a zero back EMF voltage on a selected one of the plurality of motor windings while the plurality of drive signals are stopped, the detected back EMF signal indicative of an end of the coasting time period; wherein the motor control circuit is further configured to:

- drive the plurality of motor windings with the plurality of sinusoidal current signals in a normal mode of operation in response to the detecting, wherein, in the normal mode of operation, a first cycle of a sinusoidal current signal on the selected one of the plurality of motor windings begins at zero current and at a phase continuous with a phase of the last one of the plurality of cycles of the sinusoidal current signal on the selected one of the plurality of motor windings at the end of the ramp-up time period.

34. The motor control circuit of claim 18, wherein a value of the selection signal is determined based upon a load upon the multi-phase motor.

28

35. A method of driving, with a motor control circuit, a multi-phase motor having a plurality of motor windings, the method comprising:

- receiving, from outside of the motor control circuit, a selection signal;

- identifying, with the motor control circuit, a set of parameter values from among a plurality of sets of parameter values retained on the motor control circuit, the identifying done in accordance with the selection signal;

- determining, in accordance with the identified set of parameter values, with the motor control circuit, start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings, wherein the determined start-up signal characteristics of the plurality of drive signals comprise a ramped start-up of the electric motor during a ramp-up time period during a start-up mode of operation;

- generating, with the motor control circuit, the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning; and

- receiving, from outside of the motor control circuit, a motor voltage signal, wherein the identifying the set of parameter values is done in accordance with both the selection signal and the motor voltage signal.

36. A motor control circuit for driving a multi-phase motor having a plurality of motor windings, the motor control circuit comprising a start-up control module configured to:

- receive, from outside of the motor control circuit, a selection signal;

- identify set of parameter values from among a plurality of sets of parameter values retained on the motor control circuit, the identifying done in accordance with the selection signal; and

- determine, in accordance with the identified set of parameter values, start-up signal characteristics of a plurality of drive signals coupled to the plurality of motor windings, wherein the determined start-up signal characteristics of the plurality of drive signals comprise a ramped start-up of the electric motor during a ramp-up time period during a start-up mode of operation; wherein the motor control circuit is configured to:

- generate the plurality of drive signals comprising the determined start-up signal characteristics to start the multi-phase motor spinning, wherein the start-up control module is further configured to:

- receive a motor voltage signal, and to identify the set of parameter values in accordance with both the selection signal and the motor voltage signal.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 9,281,769 B2
APPLICATION NO. : 13/893671
DATED : March 8, 2016
INVENTOR(S) : Timothy Reynolds et al.

Page 1 of 2

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the specification

Column 1, line 30 delete “particular a ramp-up” and replace with --particular ramp-up--.

Column 4, line 52 delete “but it directly” and replace with --but is directly--.

Column 4, line 57 delete “ $V_{outA}-V_{common}=V_A+IR+LdI/dt$,” and replace with
-- $V_{outA}-V_{common}=V_A+IR+LdI/dt$ --.

Column 6, line 66 delete “146b. 146c” and replace with --146b, 146c--.

Column 12, line 11 delete “on Thus,” and replace with --on. Thus,--.

Column 13, line 20 delete “704c, 704d” and replace with --704b, 704c--.

Column 15, line 39 delete “continuously other” and replace with --continuously in other--.

Column 16, line 52 delete “be this same” and replace with --be the same--.

Column 17, line 10 delete “1110 is configured” and replace with --1110 configured--.

Column 17, line 55 delete “1102a The” and replace with --1102. ¶ The--.

Column 18, line 7 delete “amp up” and replace with --ramp-up--.

Column 18, lines 19-20 delete “second d ramp-up” and replace with --second ramp-up--.

Column 20, line 4 delete “correspondents” and replace with --correspond to--.

Signed and Sealed this
Eighth Day of November, 2016



Michelle K. Lee
Director of the United States Patent and Trademark Office

CERTIFICATE OF CORRECTION (continued)

Page 2 of 2

U.S. Pat. No. 9,281,769 B2

Column 21, line 15 delete “FIG. 9)” and replace with --FIG. 9).--.

In the claims

Column 24, line 63 delete “comprising” and replace with --comprising:--.